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A STUDY OF THE OPTIMUM ROTOR GEOMETRY FOR A HIGH SPEED HELICOPTER

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prepared by:

UNITED AIRCRAFT CORPORATION
SIKORSKY AIRCRAFT DIVISION
Stratford, Connecticut

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SER-50254

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UNITED AIRCRAFT CORPORATION
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for

U. S. Army Transportation Research Command
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HEADQUARTERS
U. S. ARMY TRANSPORTATION RESEARCH COMMAND
Fort Eustis, Virginia

Under the terms of Contract DA 44-177-TC-548, Sikorsky Aircraft, Division of United Aircraft Corporation, has conducted a study to evaluate the effects of rotor blade geometry on rotor performance and stress at high forward speeds. This study is in conjunction with the efforts of the U. S. Army to improve the performance of rotary-wing aircraft.

The conclusions presented in this report are concurred in by the U. S. Army Transportation Research Command, Fort Eustis, Virginia, the cognizant agency for Contract DA 44-177-TC-548.

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ILLUSTRATIONS

SYMBOLS

A_{1_s}	lateral cyclic pitch, degrees
b	number of blades
B_{1_s}	longitudinal cyclic pitch, degrees
c	blade chord, feet
c_1	rotor blade first mode edgewise bending
c_2	rotor blade second mode edgewise bending
C_D/σ	rotor drag coefficient-solidity ratio, $D/\pi R^2 \rho (\Omega R)^2 \sigma$
C_L/σ	rotor lift coefficient-solidity ratio, $L/\pi R^2 \rho (\Omega R)^2 \sigma$
C_Q/σ	rotor torque coefficient-solidity ratio, $Q/\pi R^2 \rho (\Omega R)^2 R \sigma$
D	parasite drag, pounds
f	equivalent parasite area, square feet, D/q
f_1	rotor blade first mode flatwise bending
f_2	rotor blade second mode flatwise bending
L	rotor lift, pounds
q	free stream dynamic pressure, pounds per square foot
Q	rotor shaft torque, pound feet
r	radius to local blade station, feet
R	rotor radius, feet
V	forward speed, feet per second or knots, as appropriate

x	non-dimensional radius ratio, r/R
α	rotor angle of attack, degrees, angle between control axis and perpendicular to flight path
α_s	rotor shaft angle of attack, degrees, angle between rotor shaft and perpendicular to flight path
$\theta_{.75R}$	collective pitch angle at 75 percent rotor radius, degrees
μ	advance ratio, $V/\Omega R$
ρ	mass density of air, slugs per cubic foot
σ	rotor solidity, $bc/\pi R$
Ω	rotor angular velocity, radians per second

SUMMARY

An analytical study was performed by Sikorsky Aircraft to evaluate the effects of modifications to helicopter rotor blade geometry, including root cutout, taper, and twist, on rotor performance and vibratory blade stress at high forward speeds. It was concluded that blade twist is the most fundamental parameter and that although moderate to high twist is optimum from performance considerations, theory indicated that a low value of twist is required to minimize vibratory stresses in forward flight and thereby insure high component reliability. Wind tunnel tests were conducted on 1/8 scale model blades representative of full scale Sikorsky S-56 main blades, with linear twists of -8 and -4 degrees. The experimental results verified that the lower twist rotor blades had substantial reductions in vibratory stress at a cost of about 5 percent increase in rotor power required in high speed cruise.

The investigation was sponsored by the United States Army Transportation Research Command.

CONCLUSIONS

An analytical and experimental study of the effects of variations in helicopter rotor blade geometry on performance and vibratory blade stress at high forward speed led to the following principal conclusions:

1. Rotor blade twist is the most fundamental geometric parameter investigated influencing rotor performance. The optimum value of blade twist depends upon the rotor propulsive force required. A low value of blade twist is best from performance considerations for modern low parasite drag helicopters, whereas highly twisted rotor blades result in minimum power required only for helicopters with a high fuselage parasite drag.

2. Rotor blade twist is similarly of fundamental importance in influencing rotor blade vibratory stress. The theoretically predicted benefits of reduced blade twist were substantiated experimentally wherein significant reductions in vibratory stress levels were achieved for a -4 degree twist rotor blade in comparison to an -8 degree twist blade. Some performance penalty must be paid, however, for the increased structural reliability associated with reduced blade twist as a -4 degree twist blade requires on the order of 5 percent more horsepower than a -8 degree blade in high speed cruise.

3. Blade root cutout, inverse taper, and paddle blades offer no significant advantages in performance at high speed over a rectangular planform rotor blade.

INTRODUCTION

Recent theoretical studies such as Reference 1 have shown that substantial gains in cruise speeds and in productivity of rotary wing aircraft can be achieved relative to present day operational vehicles. To achieve such potentials a combination of good rotor efficiency and low helicopter parasite drag are required. Minimum parasite drag helicopters can be developed through careful attention to fuselage, landing gear, and rotor head design to minimize aerodynamic losses. The purpose of the present study was to evaluate a variety of rotor blade configurations to determine the optimum rotor blade geometry for high speed flight of pure helicopters. The analysis was based on a Generalized Rotor Performance method which was shown to correlate well with experimental results in Reference 2. Included in the study was an evaluation of the effects of geometry on vibratory blade stress and therefore on blade reliability. The selected rotor was tested in a wind tunnel as a dynamically scaled model and the results compared to the predictions. The investigation was sponsored by the United States Army Transportation Research Command under Contract DA 44-177-TC-548, Modification No. 1.

ANALYTICAL TECHNIQUES

Rigid Blade Theory

The theory for calculating rotor performance, described in detail in Reference 2, is a numerical integration procedure utilizing an IBM 7090 digital computer. There are no restrictions on rotor advance ratio, angle of attack, stall, or Mach number.

The airfoil section characteristics, given in Reference 2, were synthesized from hovering tests of the model rotor blades to obtain airfoil data at the proper Reynolds number. The comparison of theoretical and experimental model rotor performance over a broad range of operating conditions in Reference 2 showed that good correlation was obtained, including compressibility effects, below the theoretically predicted rotor stall boundary. Above stall the theory became highly pessimistic.

Flexible Blade Theory

The method of analyzing rotor blade stresses is an extension of the rigid blade technique described above and is covered in detail in Reference 1. The blade is represented mathematically, as shown in figure 1, by a series of rigid segments connected by pin joints and springs to provide bending stiffness equivalent to the flexible blade. The section angle of attack change due to bending is included in the calculation so that the effects of changes in aerodynamic loading, and the aerodynamic damping due to bending are automatically included in the blade stress calculation. At the time of the present study the stress calculation technique was limited to flatwise bending only - the blade is assumed to be rigid torsionally and in the inplane direction. This calculation procedure is programmed on a Philco S-2000 (Transac) digital computer.

EXPERIMENTAL EQUIPMENT AND TEST CONDITIONS

A complete description of the experimental facilities is given in Reference 2, but will be briefly reviewed herein.

Rotor Blades

The rotor blades have a nine foot diameter, a 2.69 inch chord, an NACA 0012 airfoil section, and are dynamically representative of the Sikorsky S-56 (H-37, HR2S) main rotor blades at a tip speed of 696 feet per second. The five bladed configuration used for the test provides a rotor solidity of 0.079. Figure 2 shows the component parts of a model blade. Note that the rotor blades of the present investigation are the same as in Reference 2 except that the pocket skin is 0.005 inch thick magnesium rather than the previously used paper covering. The change in material from the rotor of Reference 2 was made to insure structural integrity at greater than design rotational speeds and Mach numbers and proved to be entirely satisfactory - including operation at an advancing tip Mach number of 1.0. Because of the greater blade weight associated with the metal pockets, (15 percent heavier than in Reference 2), the rotor blade natural frequencies as shown in figure 3 are somewhat lower than for the blades of Reference 2.

Flatwise bending, chordwise bending, and torsion strain gages were located on the spar of one blade at positions shown on the accompanying table:

% Radius	Flatwise Bending	Chordwise Bending	Torsion
17.4			x
21.0	x		
33.4	x	x	
36.3			x
47.2	x	x	
63.9	x		
69.0			x
80.5	x		
90.0			x

The strain gage output for an imposed bending moment was converted to blade stress through the use of calculated spar section properties.

Due to periodic instrumentation difficulties not all of the above strain gages were functioning throughout the program.

Wind Tunnel

The United Aircraft Corporation large subsonic wind tunnel, shown in figure 4, is a closed return tunnel powered by a 9000 horsepower motor and has a maximum speed of approximately 175 knots. The test section is octagonal in cross section, 18 feet across the flats. Remote controlled air exchangers are employed to maintain constant stagnation temperature during operation.

Helicopter Rotor Test Rig

The Sikorsky Helicopter Rotor Test Rig is equipped with a six component strain gage balance and is powered by a 375 horsepower variable frequency electric motor. Figure 5a shows an overall view of the rig mounted in the wind tunnel and figure 5b shows the details of the hub and swash plate area. The five bladed rotor hub has coincident flapping and lagging hinges at 0.056 radius. Lagging motion is restrained by friction dampers and both lag and flapping motion are sensed by Clifton rotary transformers. A conventional helicopter-type swash plate is driven by three precision electric actuators which are remotely operated by a servo system in the wind tunnel control room. The tunnel yaw table provides variations in rotor shaft angle of attack. Dynamic data are recorded on a 20 channel EPSCO data acquisition system and processed automatically on an IBM 7090 digital computer.

An example of the long term repeatability of the experimental performance data is given in figure 6, which compares results of two wind tunnel tests conducted sixteen months apart on geometrically identical rotor blades. Excellent repeatability is shown. The trend for a slightly lower torque required for the test of September, 1961, compared to the data of May, 1960, is due to the fact that the all metal construction of the rotor blades for the more recent program results in a slightly lower profile drag than for the paper pocketed blades used earlier, because of reduced skin deformation under an applied airload.

Range of Test Conditions

The following range of operating conditions was investigated in the wind tunnel program:

V, knots	ΩR, feet/second	Advance Ratio, μ	Range of α_s, deg	Range of $\theta_{.75R}$, deg
125	700	0.30	-20 to 8 at 4	-4 to 14 at 2
161	700	0.39	-20 to 8 at 4	-4 to 16 at 2
161	650	0.42	-20 to 8 at 4	-6 to 18 at 2

SELECTION OF OPTIMUM ROTOR GEOMETRY

The variations in rotor blade geometry which were considered analytically are: (1) root cutout; (2) paddle blades (extended chord near blade tip); (3) taper; (4) twist.

Configurations 2 and 3 may be thought of as variations of configuration 1 and therefore will be mentioned only briefly. Reference 3 presented a brief evaluation of the performance of an idealized rotor having 100 percent chord cutout in the vicinity of the blade root. Substantial reductions in power required or increases in propulsive force capability were indicated for such a rotor at advance ratios on the order of 0.4 to 0.5 when compared to a rotor having full blade chord extending to the center of rotation. This is because of the high drag and negative lift associated with the inboard portion of the blade at the relatively high negative rotor angle of attack values required for high speed flight. Based on these results a study was made to determine whether such ideal benefits could be achieved in practice. Typical results of the analytical study are given in figure 7 for the noted condition of 161 knots forward speed, 580 feet per second tip speed, (μ = 0.47), and a disk loading of 2 pounds per square foot. The figure presents C_Q vs C_D for values of root cutout of 0, 13, 23, and 40 percent of the rotor radius. The corresponding blade geometry is sketched on the figure. The specific values of cutout were chosen to represent (1) 0 percent cutout - the idealized case of a full chord rotor blade extending to the center of rotation, (2) 13 percent cutout - corresponding to the minimum possible cutout on the S-56 considering the physical limitations of the rotor hub and feathering assembly; (3) 23 percent cutout corresponding to the radial station where the blade pockets on the S-56 begin, and (4) an arbitrarily larger 40 percent cutout. Figure 7 demonstrates that removing the inboard portion of a rotor blade does indeed result in a

large reduction in power required in comparison to a rotor blade which extends to the center of rotation. Note, however, that the greatest benefit is obtained from the region normally occupied by the rotor head and feathering assembly. However, even neglecting the gains obtained from the first 10 to 15 percent radius cutout,figure 7a shows that continued benefits are ideally derived at least out to 40 percent cutout. A more realistic evaluation is presented in figure 7b which includes the effect of a blade spar between the flapping hinge and the start of a full chord airfoil. (A two-dimensional wind tunnel test was conducted on a section of an actual S-56 spar to determine the section aerodynamic characteristics of the rotor spar for inclusion in the Generalized Rotor Performance Theory. The data are given in Reference 2.) Figure 7b shows that in the practical case, the optimum value of root cutout is in the range of 20 to 30 percent which corresponds approximately to present day Sikorsky design practice. (The calculations represented in figure 7 are for a rather low disk loading to keep the rotor generally below the predicted stall limit. However, identical calculations for a higher disk loading wherein the rotor is subjected theoretically to substantial amounts of blade stall lead to the same conclusions as to the optimum amount of root cutout for a practical rotor system.)

Two other rotor configurations which are similar to root cutout-paddle blades and inverse taper - will be discussed in conjunction with the final variable, that of blade twist. The results of theoretical calculations of the effect of blade twist on rotor power required are presented in figure 8 as torque coefficient vs blade twist for a range of parasite area at a forward speed of 161 knots, a tip speed of 700 feet per second, and a disk loading of 4 pounds per square foot. The value of blade twist for minimum power as a function of parasite area is noted on figure 8 as the Optimum Twist Envelope. The range of parasite drag, expressed as the ratio of parasite area to disk area, extends from the rather dirty $f/\pi R^2 = 0.0125$, common to present day operational aircraft to the case where the rotor provides only lift and no propulsive force ($f/\pi R^2 = 0$). Figure 8 shows that a large twist, on the order of -16 to -18 degrees is optimum from a performance standpoint only for helicopters with a high parasite drag and as the fuselage parasite drag is reduced to a value corresponding to a high performance helicopter, $f/\pi R^2 = 0.005$, the blade twist for minimum power required is about -8 to -10 degrees. Reduction in twist below the optimum value incurs some power penalties - for instance at $f/\pi R^2 = 0.005$, the -4 degree twist rotor blade theoretically requires about 5 percent more power than a -8 degree blade for the given operating condition.

The calculated performance for a rotor blade with -15 degrees twist and 1:3 inverse taper and for a -8 degree blade with a 100 percent increase in chord over the outer 20 percent radius are also noted on figure 8 as the circled and square symbols respectively and the planform is sketched on the figure. Rotor solidity is kept constant for all configurations (equivalent blade chord, defined by the relation $c_e = \int_0^1 cx^2 dx / \int_0^1 x^2 dx$, is the same for all planforms). It can be seen that no significant benefits are to be gained from the paddle or inverse taper blade planform under discussion over the more conventional rectangular planform. A detailed examination of the local angle of attack distribution for the rectangular, paddle, and inverse taper rotors shows only small differences in contour for the three configurations at a given twist and therefore there is little difference in the integrated rotor performance. Variations in rotor blade twist produce significant changes in the local angle of attack distribution, however, and similarly in power required at a given lift and drag. Similar calculations at conditions other than that shown in figure 8 lead to the same conclusions as to the effect of planform on performance.

In addition to the previously described variations in cruise power with blade twist, there is an accompanying effect of twist on hovering performance as shown theoretically in figure 9. A-15 degree twist rotor is seen to be optimum from hovering performance considerations. Thus a blade twist on the order of 10-15 degrees may be expected to provide good aerodynamic performance in both hovering and high speed flight. However, although optimizing rotor performance is of prime importance in design of a rotor system it must frequently be tempered by practical considerations of achieving high component reliability by operating dynamic components at moderate stress levels. The theoretical effect of blade twist on flatwise vibratory blade stress is given in figure 10 for a typical 63.9 percent radius station at the operating condition corresponding to the performance calculations of figure 8. Figure 10 shows that blade twist has a very powerful effect on vibratory blade stress and while a moderate to high twist may be optimum from a pure performance consideration, low twist is required to minimize stress levels. The stress levels corresponding to two values of parasite area are shown in figure 10. Although a reduction in parasite area is accompanied by an increase in stress at constant twist angle, the optimum blade twist for minimum power decreases as parasite area is reduced. Therefore, reduced drag is beneficial both from performance and from blade stress considerations.

Based on the theoretically determined compromises between minimum power required and minimum blade stress from figures 7, 8, and 10, it was concluded that the optimum rotor geometry for a high speed helicopter would be a rectangular blade with a linear blade twist of -4 degrees. Therefore two sets of rotor blades were fabricated, having the selected -4 degree twist and a conventional -8 degree twist, and tested in the wind tunnel to verify the calculations.

PRESENTATION AND DISCUSSION OF EXPERIMENTAL RESULTS

Basic rotor performance maps for each combination of forward speed, tip speed, and blade twist are presented in Appendix I. Table I lists rotor shaft angle of attack, control axis angle of attack, nominal collective pitch angle, longitudinal cyclic pitch, and lateral cyclic pitch for each data point. Correlation of theoretical and experimental model rotor performance and blade motions has been thoroughly discussed in Reference 2.

Because of the extremely large amount of blade stress data that was obtained, it is impractical to present all the basic data points. A typical plot of the basic vibratory stress data is given in figure 11 as flatwise vibratory stress amplitude versus lift coefficient-solidity ratio at constant values of rotor shaft angle of attack. The flagged symbols denote repeat points during a given run and the solid symbols denote an independent rerun. Excellent repeatability of the blade stress data is shown in figure 11. Data in the form of figure 11 were crossplotted to yield the more physically meaningful form of stress versus drag coefficient-solidity ratio at constant lift coefficient-solidity ratio and are presented in Appendix II for the complete range of operating conditions for flatwise, edgewise, and torsional modes of deflection. The major results of the experimental program are summarized below.

Effect of Blade Twist on Vibratory Stress

The variation of flatwise vibratory stress amplitude with lift coefficient solidity ratio at five radial stations is presented in figure 12 for -4 and -8 degree twist blades and a constant parasite area $f/\pi R^2 = 0.005$. These data are for forward speed/tip speed combinations of 125 knots/700 feet per second, 161 knots/700 feet per second, and 161 knots/650 feet per second. A pronounced correspondence between increased rotor lift and increased stress levels is demonstrated at all radial stations and the predicted reduction in

vibratory stress with reduced blade twist is seen to be achieved experimentally in almost all instances. It is believed that the rather small influence of blade twist on vibratory stress at the 20 percent radius station is due to the proximity of the relatively heavy mass of the blade feathering assembly. Flexure of the blade at the most inboard location is influenced more by the inertial forces on the heavy root mass than the aerodynamic loading, which is the primary parameter over the outer portion of the radius. The effect is not significant however because the stress levels are low and therefore of less importance at the inboard location. The reduction in stress with twist is generally on the order of 500 to 1000 pounds per square inch and about the same amount at forward speeds of 125 and 161 knots. A given decrement in stress is more significant from considerations of blade reliability however, at the higher forward speed where the general stress level is higher.

Figure 13 compares the chordwise blade stress for both rotor blades in the same form as in figure 12. When data are shown for only one blade twist in this and subsequent figures it is a result of failures of the strain gages on the particular blade during testing. The plotted chordwise stress corresponds to the leading edge of the rotor blade (The stress at the rear of the blade spar is equal to 0.7 of the leading edge value due to a closer proximity to the neutral axis of the spar.) At 650 feet per second tip speed the -4 degree twist rotor blade exhibits a lower chordwise stress than the -8 degree blade as would be expected, but at the same forward speed and 700 feet per second tip speed the -4 degree twist has significantly greater chordwise stress than the -8 degree blade. Figure 14 presents both flatwise and chordwise vibratory stress at 47 percent radius for a larger parasite area, $f/\pi R^2 = 0.01$. Figure 14b, as did figure 13, also shows a greater chordwise stress level for the lower twist rotor blade at 700 feet per second tip speed. An examination of the measured rotor blade lagging motion showed that while the steady lag angle was essentially the same at 650 and 700 feet per second for the -4 degree twist rotor blades, there was a large oscillatory lag motion at 650 feet per second and essentially no hunting at 700 feet per second and 161 knots forward speed. As mentioned in the section "Description of Equipment" rotor blade lag motion is restrained by spring loaded friction dampers located on the rotor head. While these friction dampers are entirely adequate to suppress mechanical instabilities such as ground resonance they are not satisfactory overall in that it is extremely difficult to set and maintain a constant damping moment. From an examination of the rotor blade hunting records it is believed that the lag damping moment was at a normal value for most conditions, where there was appreciable lag motion, but for the -4 degree twist blades at 700 feet per second and 161 knots forward speed the damping

was so excessively high that the rotor blades were restricted from lagging. Such edgewise root restraint would result in the large vibratory chordwise stresses of figure 13a and 14b for the -4 degree twist rotor blade. Also, because the damping moment is about an axis parallel to the rotor shaft and the rotor blades are both twisted and tilted to some collective pitch angle, there is a component of the damping moment in the flatwise bending direction which could account for a relatively high flatwise bending stress of the -4 degree rotor blade at 161 knots and 700 feet per second tip speed. Therefore, it is felt that the comparative effects of twist on stress at the latter condition are not as realistic as for the two remaining operating conditions. Since the time of the investigation reported herein, small viscous lag hinge dampers have been developed for the Sikorsky Helicopter Rotor Test Rig so that future stress measurements will not be influenced by the mechanical limitations described above.

Effect of Rotor Lift and Propulsive Force on Blade Stress

The effect of lift on flatwise bending stress at constant parasite area was discussed in connection with figure 12 and can also be seen from figure 15, which presents flatwise vibratory blade stress versus drag coefficient-solidity ratio at constant values of lift coefficient-solidity ratio. Figure 15 also shows that the theoretically predicted effect of rotor propulsive force on stress at constant lift and blade twist - that is, that an increased propulsive force corresponding to a higher parasite drag results in a reduction in vibratory stress level - is borne out experimentally. However, as discussed in connection with figures 8 and 10 it is always desirable to minimize the rotor propulsive force required by minimizing parasite drag when the interrelationship of twist, power required, parasite drag, and blade stresses are considered.

Effect of Blade Twist on Rotor Performance

The experimental effects of blade twist on rotor performance are presented in figure 16 as C_Q/σ vs. C_D/σ at two typical values of C_L/σ and substantiate the analytical results of figure 8. A typical range of C_D/σ for pure helicopter operation is noted in figure 16 for each condition. The blade twist for minimum power depends on the rotor propulsive force required. At 125 knots where the required propulsive force is small the -4 degree twist blade is equal to or superior to the -8 degree configuration. However, at a high forward speed of V = 161 knots, where the propulsive force requirements are greater the reduced twist rotor incurs a penalty in power required on the order of five percent.

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TABULATED ROTOR BLADE MOTIONS

	α_s, deg	α, deg	$\theta_{.75R}$, deg	A_{1s}, deg	B_{1s}, deg
Condition I	-20	-25.2	10	.3	5.2
		-27.3	12	- .7	7.3
V = 161 kt		-28.9	14	-2.1	9.0
ΩR = 700 ft/sec		-30.4	16	-3.5	10.5
μ = .39		-31.2	17	-4.0	11.3
θ_1 = -8 deg		-28.6	14	-1.7	8.7
		-25.4	10	- .4	5.4
	-16	-20.7	8	0	4.7
		-22.5	10	- .5	6.5
		-24.6	12	-1.4	8.7
		-26.0	14	-2.8	10.1
		-27.4	16	-4.1	11.5
		-24.5	12	-1.4	8.6
		-22.7	10	-0.4	6.7
	-16	-20.8	8	.5	4.8
		-22.3	10	- .3	6.3
		-24.2	12	-1.5	8.3
		-25.7	14	-2.5	9.8
		-27.5	16	-3.7	11.6
		-28.3	17	-4.4	12.4
		-24.2	12	-1.2	8.3
		-22.2	10	-0.3	6.2
	-12	-16.6	6	.3	4.6
		-18.1	8	- .5	6.2
		-19.9	10	-1.2	8.0
		-21.6	12	-2.5	9.7
		-23.3	14	-3.4	11.4
		-24.0	15	-4.0	12.1
		-21.2	12	-2.2	9.3
		-18.1	8	- .5	6.1

	α_s, deg	α, deg	$\theta_{.75R}$, deg	A_{1s}, deg	B_{1s}, deg
Condition I (continued)	-8	-11.8	4	0.4	3.8
		-13.6	6	-.5	5.6
		-15.2	8	-.8	7.3
		-16.8	10	-2.0	8.9
		-18.9	12	-2.8	11.0
		-12.2	14	-4.0	4.3
		-16.6	10	-2.0	8.7
		-13.4	6	0	5.4
	-4	-7.1	2	.3	3.1
		-8.7	4	-.5	4.8
		-10.5	6	-1.1	6.6
		-12.5	8	-1.6	8.6
		-14.0	10	-2.7	10.1
		-15.9	12	-3.2	12.0
		-12.1	8	-1.5	8.2
		-9.0	4	-.2	5.1
	0	-.3	-2	1.2	.3
		-2.4	0	.5	2.5
		-4.6	2	-.3	4.7
		-5.9	4	-.8	6.0
		-8.2	6	-1.2	8.3
		-4.2	2	-.3	4.3
		-.3	-2	1.1	.3
	0	-.4	-2	1.1	.4
		-2.8	0	.6	2.8
		-4.2	2	-.1	4.3
		-6.2	4	-.7	6.3
		-8.3	6	-1.3	8.4
		-4.3	2	0.1	4.4
		-.6	-2	1.1	.6

	α_s, deg	α, deg	$\theta_{.75R}$, deg	A_{1s}, deg	B_{1s}, deg
Condition I (continued)	4	4.2	-4	1.1	-.2
		2.2	-2	.6	1.8
		.2	0	0	3.7
		-1.0	2	-.4	5.1
		-3.0	4	-.8	7.1
		-5.3	6	-1.2	9.4
		-1.5	2	-.4	5.6
		2.3	-2	.7	1.7
	8	9.3	-6	.8	-1.4
		6.7	-4	.9	1.3
		4.6	-2	.1	3.4
		2.9	0	-.4	5.1
		.8	2	-.9	7.2
		-.7	4	-.9	8.8
		5.4	-2	.2	2.6
		6.9	-4	.8	1.1
Condition II	-20	-26.8	12	0	6.8
		-28.3	14	-1.0	8.4
V = 161 kt		-29.8	16	-2.5	9.9
ΩR = 650 ft/sec		-31.9	18	-3.9	12.0
μ = .42		-28.6	14	-1.0	8.7
θ_1 = -8 deg		-26.8	12	.1	6.8
	-16	-22.2	10	-.1	6.2
		-23.6	12	-.7	7.7
		-25.9	14	-2.1	10.0
		-27.6	16	-3.4	11.7
		-29.3	18	-5.1	13.4
		-27.6	16	-3.3	11.7
		-24.1	12	-1.1	8.1

	α_s, deg	α, deg	$\theta_{.75R}$, deg	A_{1s}, deg	B_{1s}, deg
Condition II (continued)	-12	-15.5	6	- .6	3.5
		-17.6	8	.1	5.6
		-19.7	10	- .9	7.8
		-20.8	12	-2.1	8.9
		-22.5	14	-3.0	10.6
		-24.7	16	-4.7	12.8
		-25.4	17	-5.3	13.5
		-22.9	14	-3.1	11.0
		-19.4	10	-1.0	7.5
	- 8	-12.0	4	.7	4.0
		-13.7	6	0	5.8
		-15.6	8	- .9	7.7
		-17.5	10	-1.8	9.6
		-18.6	12	-2.7	10.7
		-20.1	14	-3.9	12.2
		-22.8	16	-5.0	14.9
		-16.8	10	-1.4	8.9
		-13.6	6	0	5.7
	- 4	- 4.6	0	1.3	.6
		- 7.2	2	.6	3.2
		- 9.3	4	- .1	5.4
		-11.0	6	- .4	7.1
		-12.4	8	-1.4	8.5
		-14.6	10	-2.3	10.7
		-16.2	12	-3.2	12.3
		-12.1	8	-1.2	8.2
		- 8.6	4	.1	4.7
	0	.5	- 3	1.9	- .6
		0	- 2	1.4	- .1
		- 2.7	0	1.0	2.7
		- 4.5	2	0	4.6
		- 6.4	4	- .3	6.5
		- 7.9	6	- .9	8.0
		- 9.9	8	-1.5	10.0
		-11.7	10	-2.6	11.8
		- 7.9	6	- .9	8.0
		- 2.4	0	.9	2.4

	α_s, deg	α, deg	$\theta_{.75R}$, deg	A_{1s}, deg	B_{1s}, deg
Condition II (continued)	4	6.8	- 6	1.9	- 2.9
		4.3	- 4	1.4	- .3
		2.5	- 2	.9	1.5
		.1	0	.2	3.9
		- 1.8	2	- .3	5.9
		- 3.5	4	- .7	7.6
		- 5.2	6	-1.5	9.3
		- 6.9	8	-2.1	11.1
		- 3.6	4	- .5	7.7
		2.1	- 2	1.2	1.9
	8	4.8	- 8	1.9	- 3.1
		9.6	- 6	1.1	- 1.7
		7.0	- 4	.9	1.0
		5.1	- 2	.5	2.9
		2.8	0	0	5.2
		.8	2	- .7	7.2
		- .8	4	-1.0	8.9
		- 2.3	6	-1.7	10.4
		1.0	2	- .6	7.0
		7.4	- 4	.6	.6
Condition III	-20	- 23.8	8	0	3.8
		- 25.2	10	- .7	5.2
V = 125 kt		- 26.6	12	-1.9	6.7
ΩR = 700 ft/sec		- 28.5	14	-3.1	8.7
μ = .30		- 30.1	16	-4.1	10.3
θ_1 = -8 deg		- 26.6	12	-1.9	6.7
		- 23.9	8	.1	3.9
	-16	- 19.3	6	- .1	3.3
		20.5	8	- .8	4.6
		22.2	10	-1.7	6.3
		23.6	12	-2.5	7.8
		25.5	14	-3.8	9.7
		29.1	15.5	-4.7	13.3
		23.4	12	-2.8	7.6
		20.5	8	- 5	4.6

	α_s, deg	α, deg	$\theta_{.75R}$, deg	A_{1s}, deg	B_{1s}, deg
Condition III (continued)	-12	-14.6	4	- .1	2.6
		-16.3	6	- .8	4.3
		-17.9	8	-1.3	6.0
		-19.3	10	-2.4	7.5
		-20.7	12	-3.5	8.9
		-22.7	14	-4.2	10.9
		-23.7	15	-4.5	11.9
		-21.0	12	-3.4	9.2
		-16.4	6	- .5	4.4
	- 8	- 9.7	2	.3	1.7
		-11.4	4	- .3	3.4
		-13.2	6	-1.2	5.3
		-14.9	8	-1.6	7.0
		-16.1	10	-2.9	8.3
		-18.4	12	-3.5	10.6
		-20.2	14	-4.2	12.4
		-21.0	15	-4.8	13.2
		-16.2	10	-3.0	8.4
		-11.3	4	- .4	3.3
	- 4	- 5.0	0	.6	1.0
		- 7.1	2	0	3.1
		- 8.7	4	- .8	4.8
		-10.5	6	-1.5	6.6
		-12.5	8	-2.7	8.7
		-13.7	10	-3.2	9.9
		-15.7	12	-3.6	11.9
		-17.3	14	-4.4	13.5
		-13.2	10	-3.0	9.4
		- 8.0	4	- .9	4.1
	0	- .1	- 2	.8	.1
		- 2.0	0	0	2.1
		- 3.6	2	- .7	3.7
		- 5.3	4	-1.5	5.4
		- 6.8	6	-2.2	7.0
		- 8.7	8	-2.8	8.9
		-10.6	10	-3.5	10.8
		- 7.2	6	-1.8	7.4
		- 3.6	2	- .7	3.7

	α_s, deg	α, deg	$\theta_{.75R}$, deg	A_{1s}, deg	B_{1s}, deg
Condition III (continued)	4	5.1	-4	.9	-1.2
		3.0	-2	.2	1.0
		.9	0	-.6	3.1
		-.3	2	-1.2	4.4
		-1.9	4	-1.6	6.1
		-3.8	6	-2.3	8.0
		-5.8	8	-2.8	10.0
		-7.9	10	-3.3	12.1
		-2.2	4	-1.3	6.4
		3.0	-2	.3	1.0
	8	10.1	-6	.8	-2.2
		8.0	-4	.5	0
		6.3	-2	-.2	1.7
		4.6	0	-.8	3.5
		2.1	.2	-1.3	6.0
		.4	4	-1.6	7.7
		-1.2	6	-2.1	9.4
		-2.4	8	-3.0	10.6
		.7	4	-1.8	7.4
		3.9	0	-.7	4.1
Condition IV	-20	-26.5	12	-.2	6.5
		-28.6	14	-1.5	8.7
V = 161 kt		-30.8	16	-3.1	10.9
ΩR = 700 ft/sec		-32.2	17	-3.7	12.3
μ = .39		-32.0	18	-3.8	12.1
θ_1 = -4 deg		-28.9	14	-1.4	9.0
		-26.9	12	-.3	6.9
	-16	-22.6	10	-.3	6.6
		-23.9	12	-1.5	8.0
		-26.4	14	-2.6	10.5
		-28.5	16	-3.6	12.2
		-26.3	14	-2.6	10.4
		-22.1	10	-.1	6.1

	α_s, deg	α, deg	$\theta_{.75R}$, deg	A_{1s}, deg	B_{1s}, deg
Condition IV (continued)	-12	-14.3	4	.6	2.3
		-16.4	6	.1	4.4
		-18.5	8	-.5	6.5
		-20.3	10	-1.1	8.4
		-22.2	12	-2.1	10.3
		-24.0	14	-2.9	12.1
		-20.2	10	-1.3	8.2
		-16.4	6	-.1	4.4
	-8	-11.5	4	.3	3.5
		-13.4	6	-.5	5.5
		-15.5	8	-1.3	7.6
		-17.5	10	-2.1	9.6
		-19.1	12	-2.8	11.2
		-21.0	14	-3.3	13.1
		-17.4	10	-2.1	9.5
		-13.8	6	-.4	5.9
	-4	-4.1	0	1.1	.1
		-7.2	2	.6	3.2
		-9.2	4	0	5.3
		-10.9	6	-.8	7.0
		-13.1	8	-1.3	9.2
		-14.5	10	-1.2	10.6
		-16.3	12	-2.0	12.4
		-14.6	10	-1.6	10.7
		-8.7	4	0	4.8
	0	-.9	-2	.9	.9
		-3.2	0	.4	3.2
		-5.0	2	-.5	5.1
		-6.8	4	-1.1	6.9
		-8.7	6	-1.6	8.8
		-10.5	8	-2.0	10.6
		-7.0	4	-.8	7.1
		-3.4	0	.4	3.4

	α_s, deg	α, deg	$\theta_{.75R}$, deg	A_{1s}, deg	B_{1s}, deg
Condition IV (continued)	4	5.0	-4	1.2	-1.1
		2.2	-2	.8	1.8
		.4	0	.1	3.6
		-1.8	2	-.5	5.9
		-3.6	4	-.7	7.7
		-5.1	6	1.4	9.2
		-6.2	7	-1.4	10.3
		-1.7	2	-.6	5.8
		2.5	-2	.6	1.5
	8	8.7	-6	.7	-.8
		6.3	-4	.5	1.7
		4.1	-2	-.2	3.9
		2.2	0	-.4	5.8
		.4	2	-.5	7.6
		-1.3	4	-.5	9.4
		-2.8	6	-.5	10.9
		-5.2	8	-.3	13.3
		.8	2	-.7	7.2
		6.3	-4	.4	1.6
Condition V	-20	-26.5	12	-.3	6.5
		-28.4	14	-1.5	8.4
V = 161 kt		-30.5	16	-2.7	10.6
ΩR = 650 ft/sec		-32.2	18	-4.0	12.3
μ = .42		-30.6	16	-2.5	10.7
θ_1 = -4 deg		-26.6	12	-.1	6.6
	-16	-22.4	10	-.3	6.4
		-24.2	12	-1.3	8.3
		-26.2	14	-2.2	10.3
		-28.1	16	-3.5	12.2
		-29.9	18	-3.4	14.0
		-26.3	14	-2.0	10.4
		-22.3	10	0	6.3

	α_s, deg	α, deg	$\theta_{.75R}$, deg	A_{1s}, deg	B_{1s}, deg
Condition V (continued)	-12	-15.8	6	.3	3.8
		-17.9	8	-.2	5.9
		-19.9	10	-1.1	8.0
		-21.9	12	-2.3	10.0
		-23.6	14	-3.2	11.7
		-25.5	16	-3.2	13.6
		-21.7	12	-2.0	9.8
		-15.8	6	.3	3.8
	-8	-11.8	4	.1	3.8
		-13.8	6	-.7	5.8
		-15.7	8	-.7	7.8
		-17.8	10	-1.9	9.9
		-19.5	12	-2.4	11.6
		-21.3	14	-2.6	13.4
		-17.7	10	-1.7	9.8
		-13.8	6	-.2	5.8
	-4	-5.5	0	1.1	1.5
		-7.7	2	1.5	3.7
		-9.6	4	-.2	5.7
		-11.5	6	-.6	7.6
		-13.6	8	-1.8	9.7
		-15.4	10	-1.8	11.5
		-17.2	12	-2.0	13.3
		-14.9	10	-1.6	11.0
		-9.3	4	-.2	5.4
	0	-.7	-2	1.1	.7
		-3.1	0	.6	3.1
		-5.3	2	0	5.4
		-7.3	4	-.8	7.4
		-8.9	6	-1.1	9.0
		-10.6	8	-1.9	10.7
		-12.1	10	-2.4	12.2
		-13.8	12	-2.5	13.9
		-10.4	8	-1.4	10.5
		-6.9	4	-.7	7.0

	α_s, deg	α, deg	$\theta_{.75R}$, deg	A_{1s}, deg	B_{1s}, deg
Condition V (continued)	4	6.6	-6	1.8	-2.7
		4.0	-4	1.2	-.1
		1.5	-2	.8	2.5
		0	0	.1	4.1
		-2.5	2	-.6	6.6
		-3.8	4	-1.1	7.9
		-5.9	6	-1.3	10.0
		-7.7	8	-1.3	11.8
		-4.2	4	-.7	8.3
		-.1	0	-.1	4.2
	8	8.8	-6	-1.1	-.8
		6.4	-4	.6	1.6
		4.1	-2	-.1	3.9
		2.2	0	-.2	5.8
		.9	2	-.7	7.1
		-.8	4	-.9	8.9
		-1.6	5	-.9	9.7
		.9	2	-.5	7.1
		4.3	-2	-.1	3.7
Condition VI	-20	-23.9	8	-.2	3.9
		-25.7	10	1.0	5.7
V = 125 kt		-27.3	12	-2.2	7.4
ΩR = 700 ft/sec		-29.0	14	-4.0	9.2
μ = .30		-27.5	12	-2.2	7.6
θ_1 = -4 deg		-25.6	10	1.4	5.6
	-16	-19.3	6	-.1	3.3
		-20.9	8	.9	4.9
		-22.8	10	-1.8	6.9
		-24.5	12	-3.3	8.7
		-26.0	14	-4.1	10.2
		-22.5	10	-2.1	6.6
		-21.1	8	-1.0	5.1

	α_s, deg	α, deg	$\theta_{.75R}$, deg	A_{1s}, deg	B_{1s}, deg
Condition VI (continued)	-12	-14.4	4	.3	2.4
		-16.4	6	-.5	4.4
		-17.8	8	-1.5	5.9
		-19.8	10	-2.8	7.9
		-21.5	12	-3.6	9.7
		-23.0	14	-4.2	11.2
		-19.6	10	-2.8	7.7
		-16.4	6	-.9	4.4
	-8	-9.5	2	.5	1.5
		-11.3	4	-.5	3.3
		-13.2	6	-1.1	5.3
		-15.0	8	-2.2	7.1
		-16.8	10	-3.2	9.0
		-18.6	12	-3.5	10.8
		-16.9	10	-3.1	9.1
		-13.4	6	1.3	5.5
	-4	-4.9	0	.7	.9
		-6.8	2	-.3	2.8
		-8.6	4	-1.1	4.7
		-10.3	6	-1.8	6.4
		-12.0	8	-2.5	8.2
		-14.0	10	-3.0	10.2
		-15.5	11	-3.2	11.7
		-12.0	8	-2.8	8.2
		-8.6	4	-.9	4.7
	0	.2	-2	1.2	-.3
		-2.1	0	.1	2.1
		-4.0	2	-.8	4.1
		-5.9	4	-1.7	6.0
		-7.4	6	-2.6	7.6
		-9.4	8	-2.7	9.6
		-6.0	4	-1.6	6.1
		-2.6	0	0	2.6

Condition VI (continued)	α_s, deg	α, deg	$\theta_{.75R}$, deg	A_{1s}, deg	B_{1s}, deg
	4	4.9	-4	1.0	-1.0
		2.6	-2	.5	1.4
		.5	0	-.8	3.5
		1.3	2	-1.5	5.4
		-2.8	4	-2.1	7.0
		-4.4	6	-2.5	8.6
		-6.4	8	-2.5	10.6
		-2.7	4	-1.8	6.9
		2.5	-2	.4	1.5
	8	10.1	-6	1.1	-2.2
		7.6	-4	.4	.3
		5.4	-2	-.3	2.6
		3.7	0	-1.1	4.3
		1.9	2	-1.6	6.2
		.4	4	-2.1	7.7
		-1.2	6	-2.1	9.4
		2.0	2	-1.6	6.1
		5.5	-2	-.3	2.5

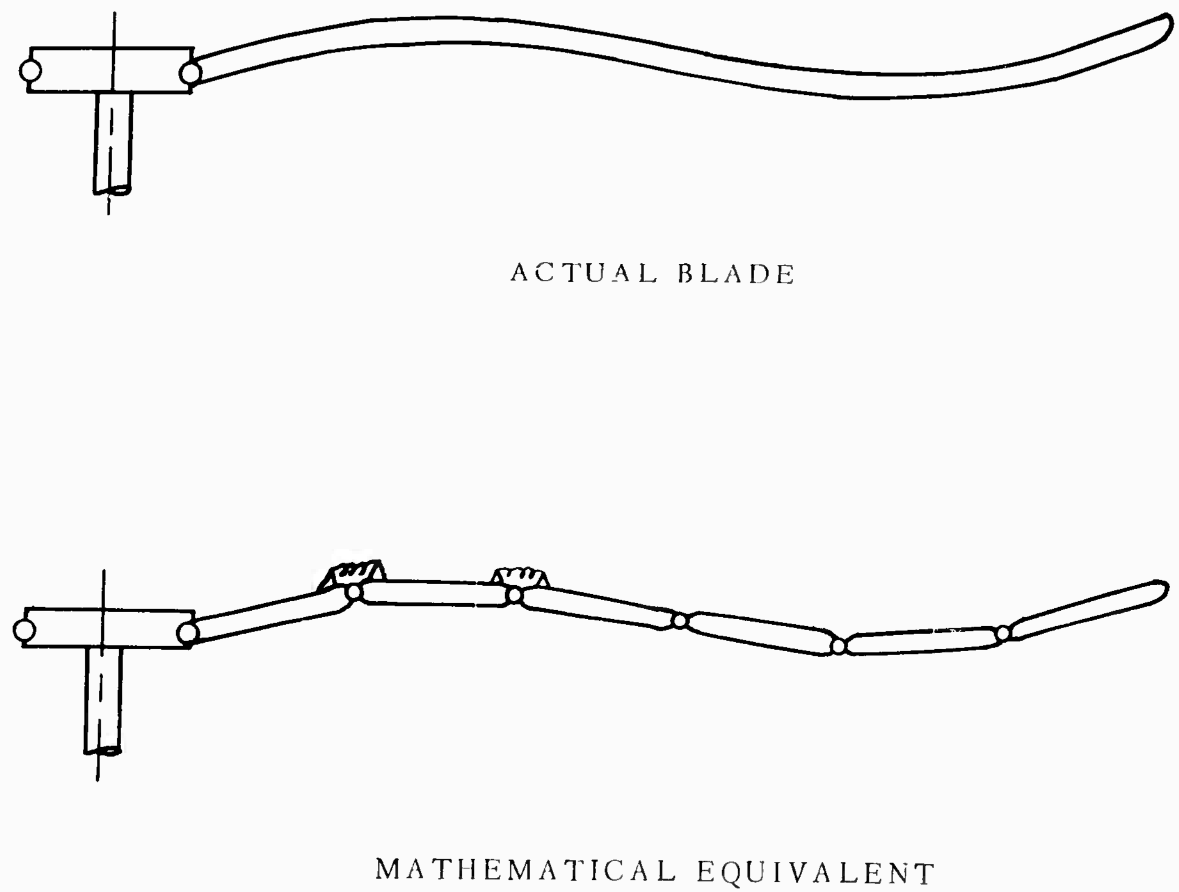


FIG. 1. MATHEMATICAL REPRESENTATION OF FLEXIBLE BLADE

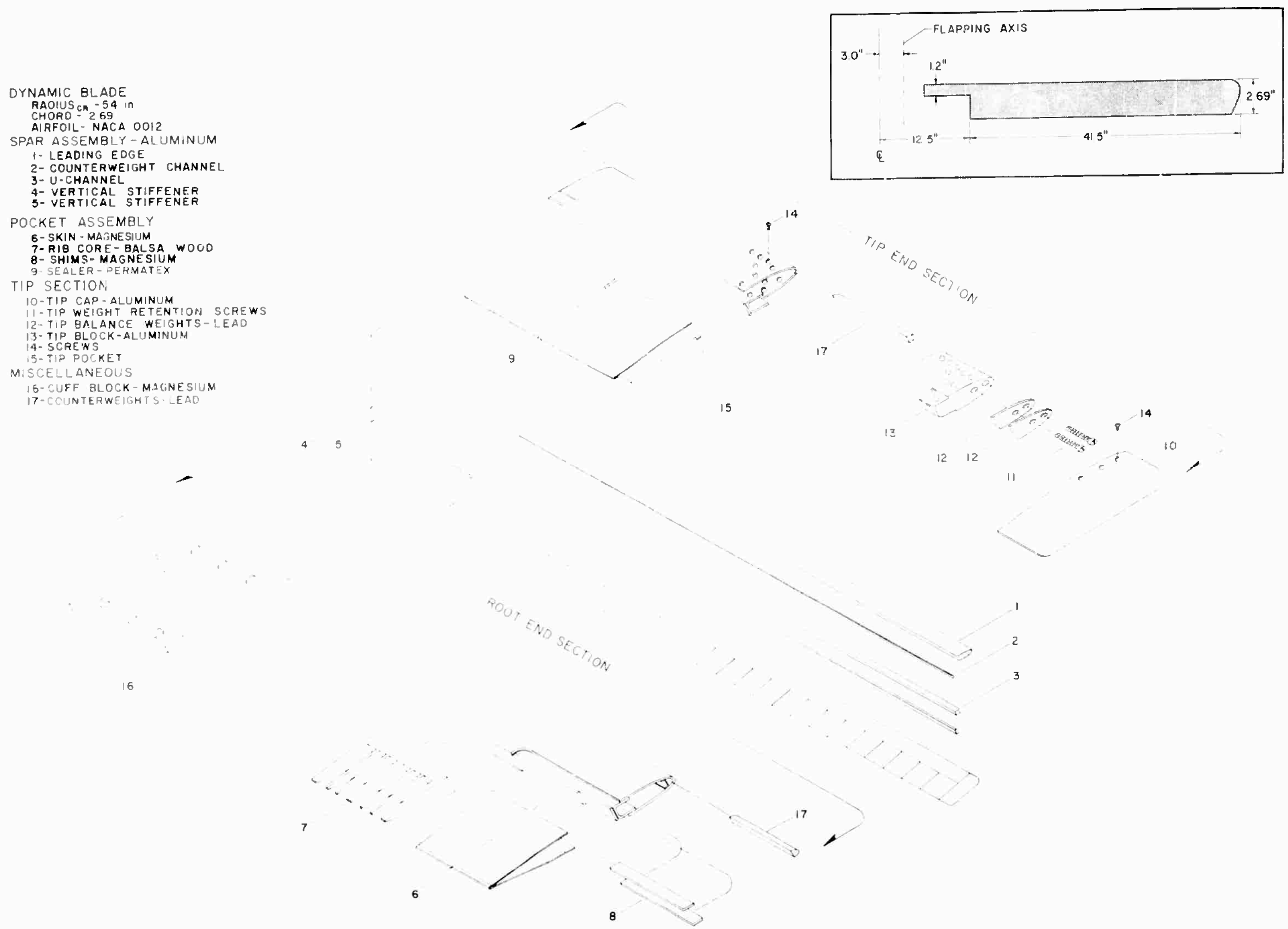


FIG. 2. DYNAMICALLY SCALED BLADE - EXPLODED VIEW

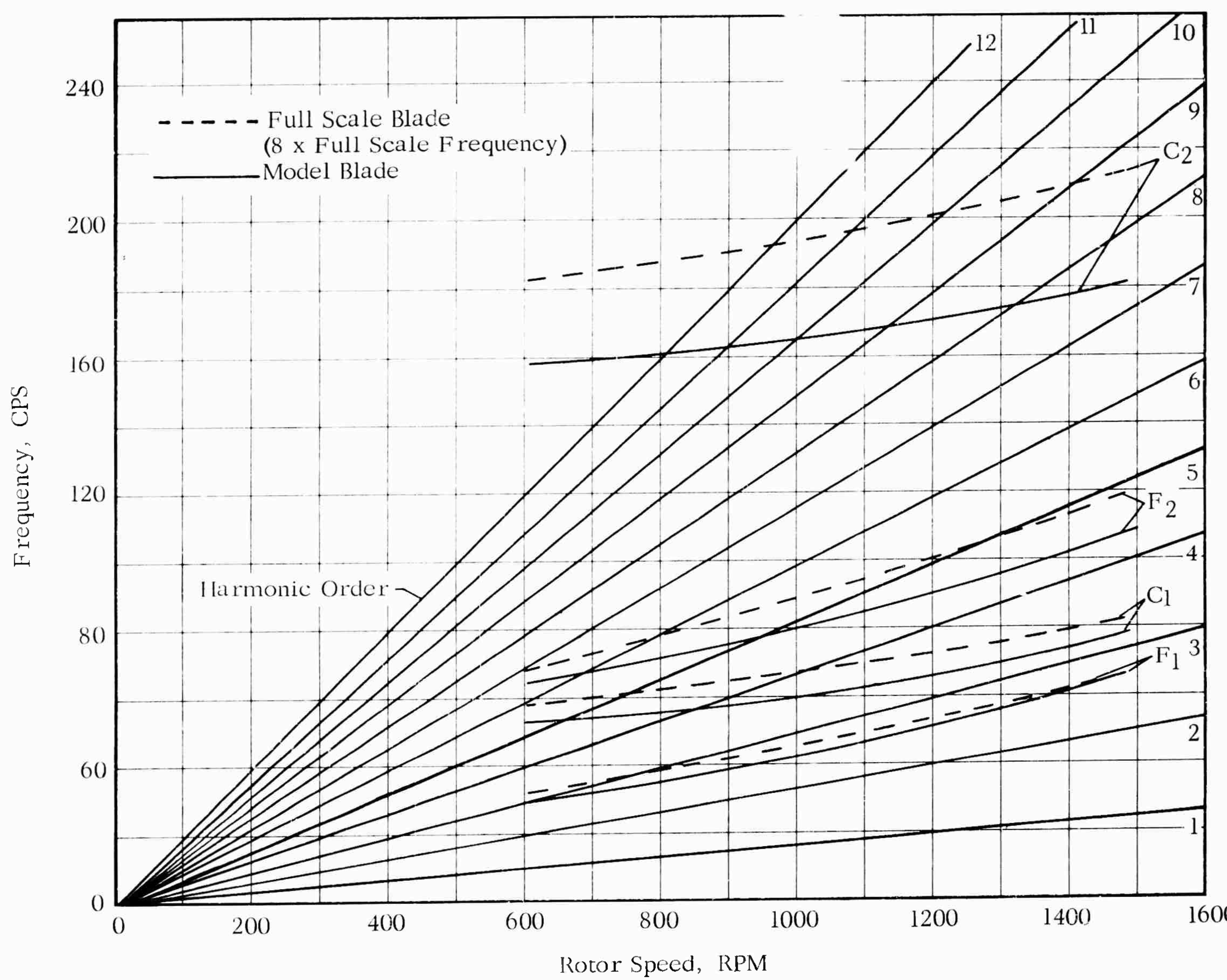


FIG. 3. COMPARISON OF MODEL AND FULL SCALE ROTOR BLADE NATURAL FREQUENCIES

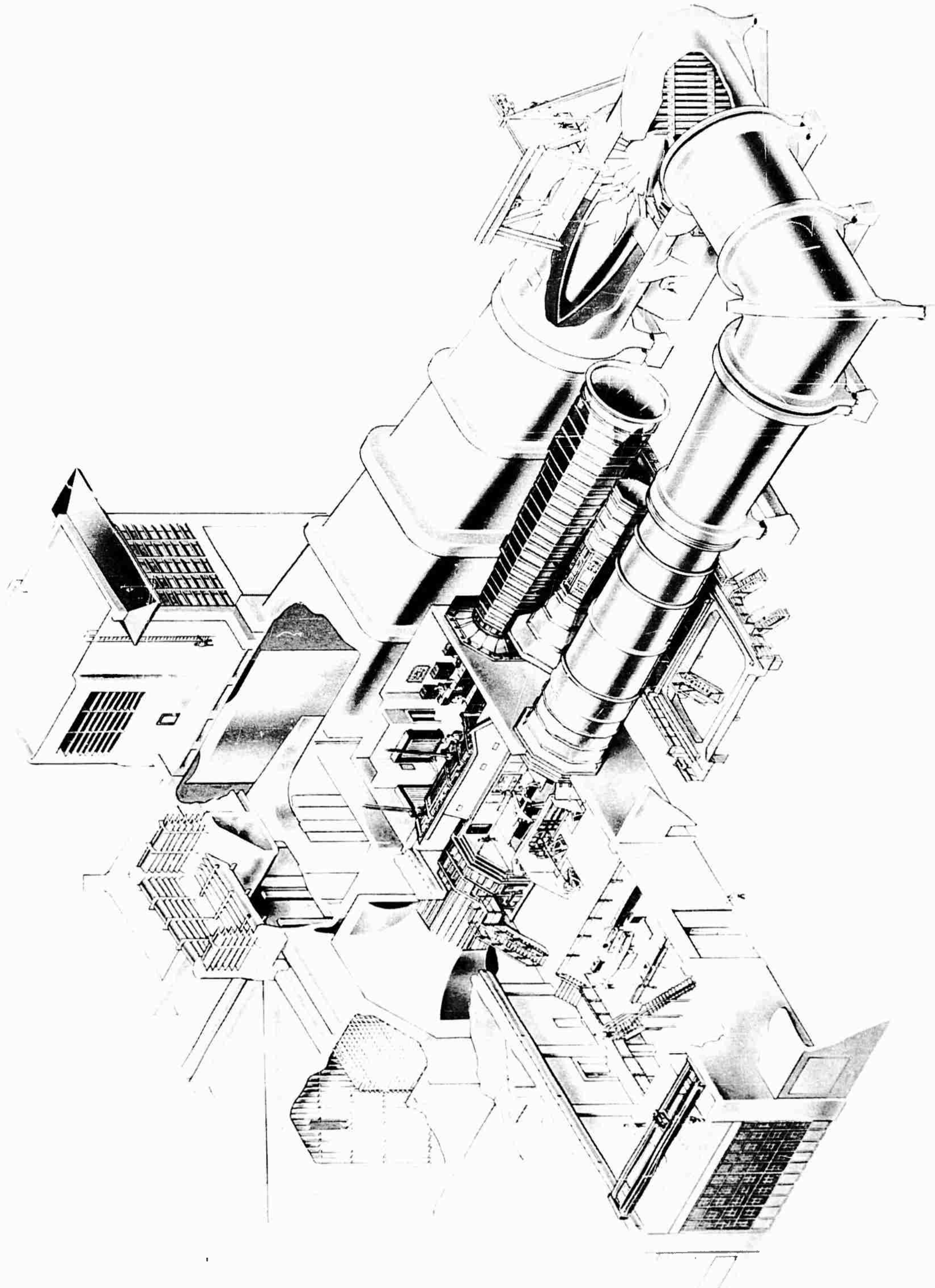
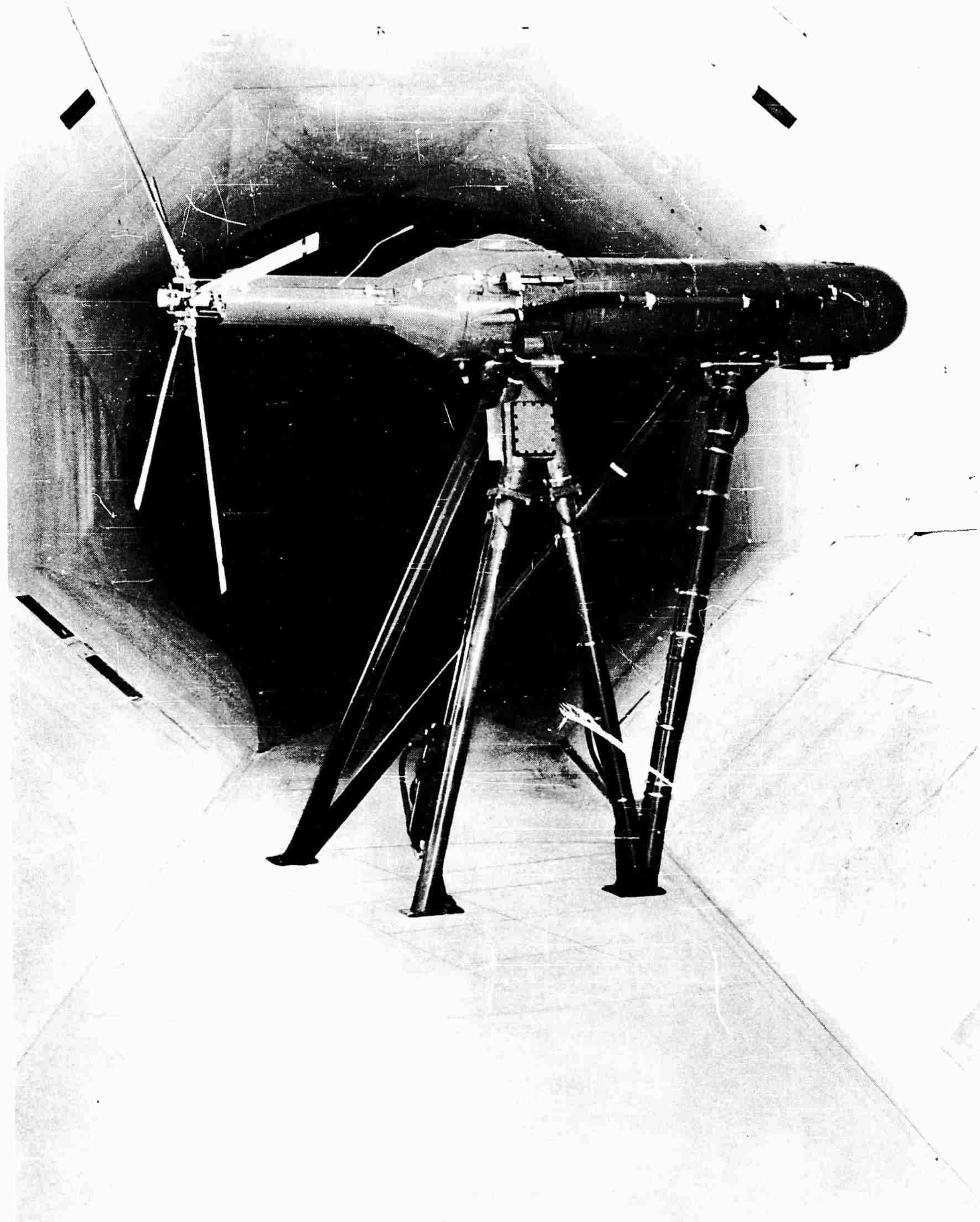
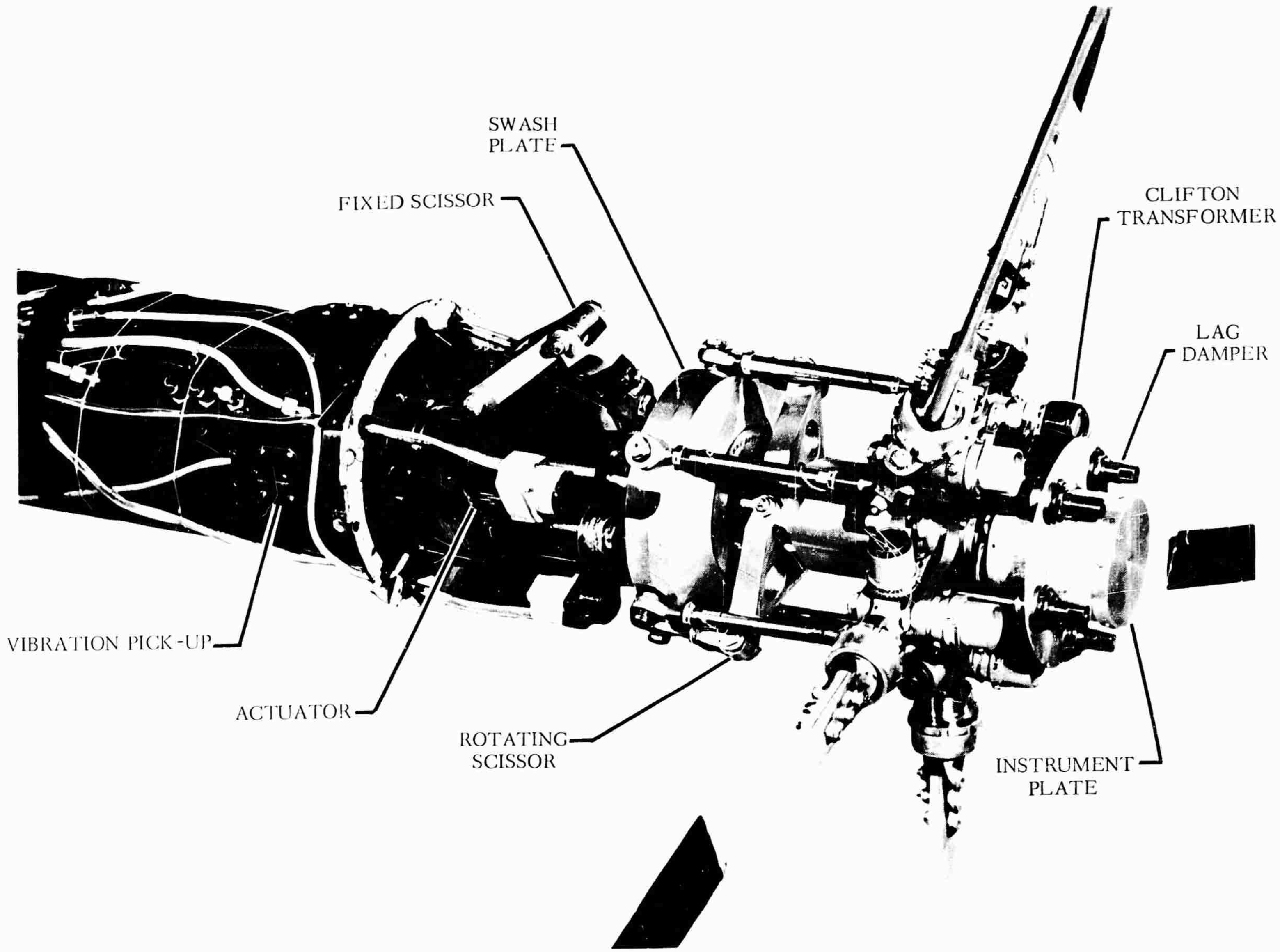


FIG. 4. UNITED AIRCRAFT SUBSONIC WIND TUNNEL



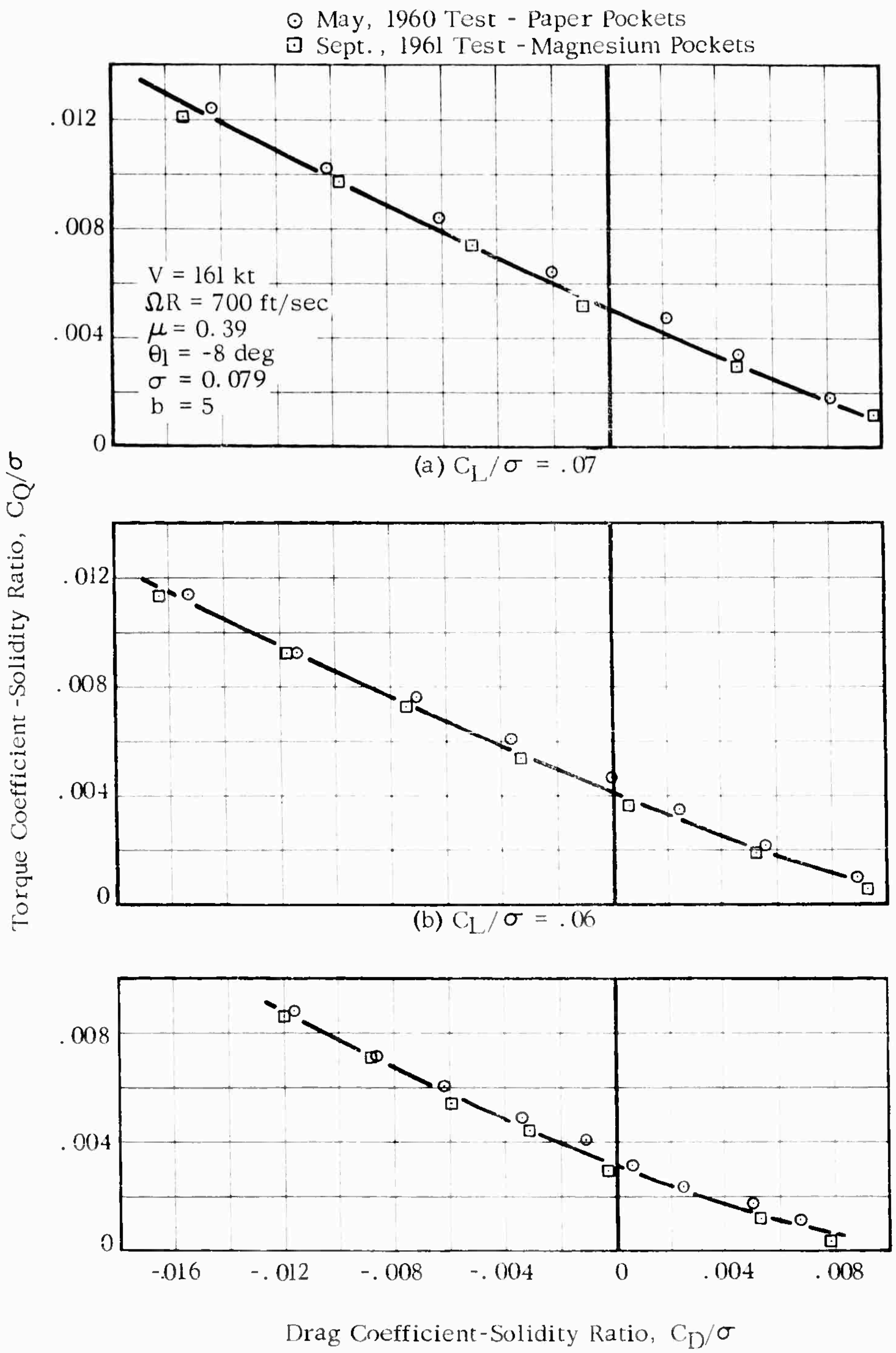
(a) General View of Model Installation in Wind Tunnel

FIG. 5. SIKORSKY HELICOPTER ROTOR TEST RIG



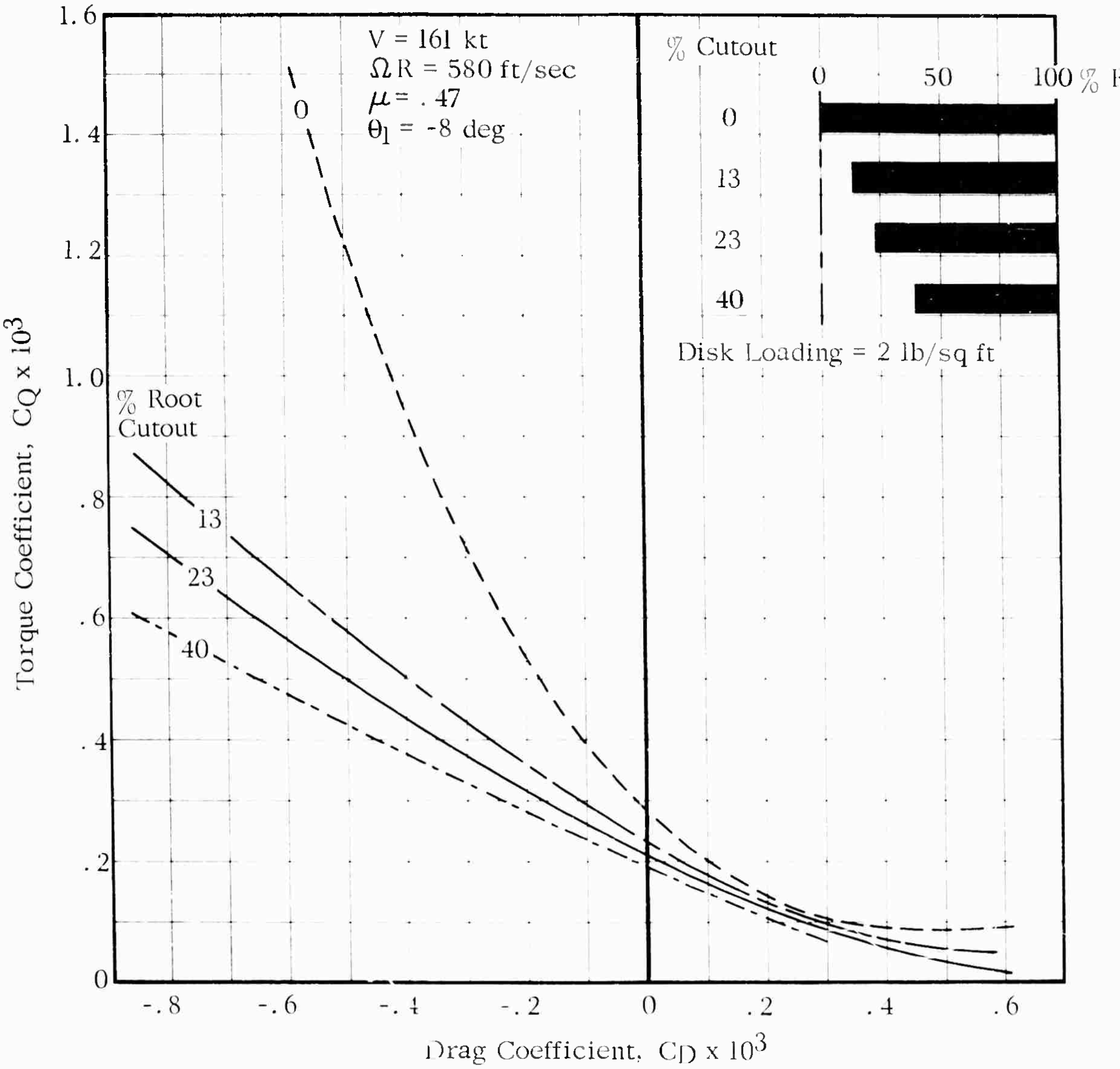
(b) Details of Hub and Swash Plate Area

FIGURE 5 CONCLUDED



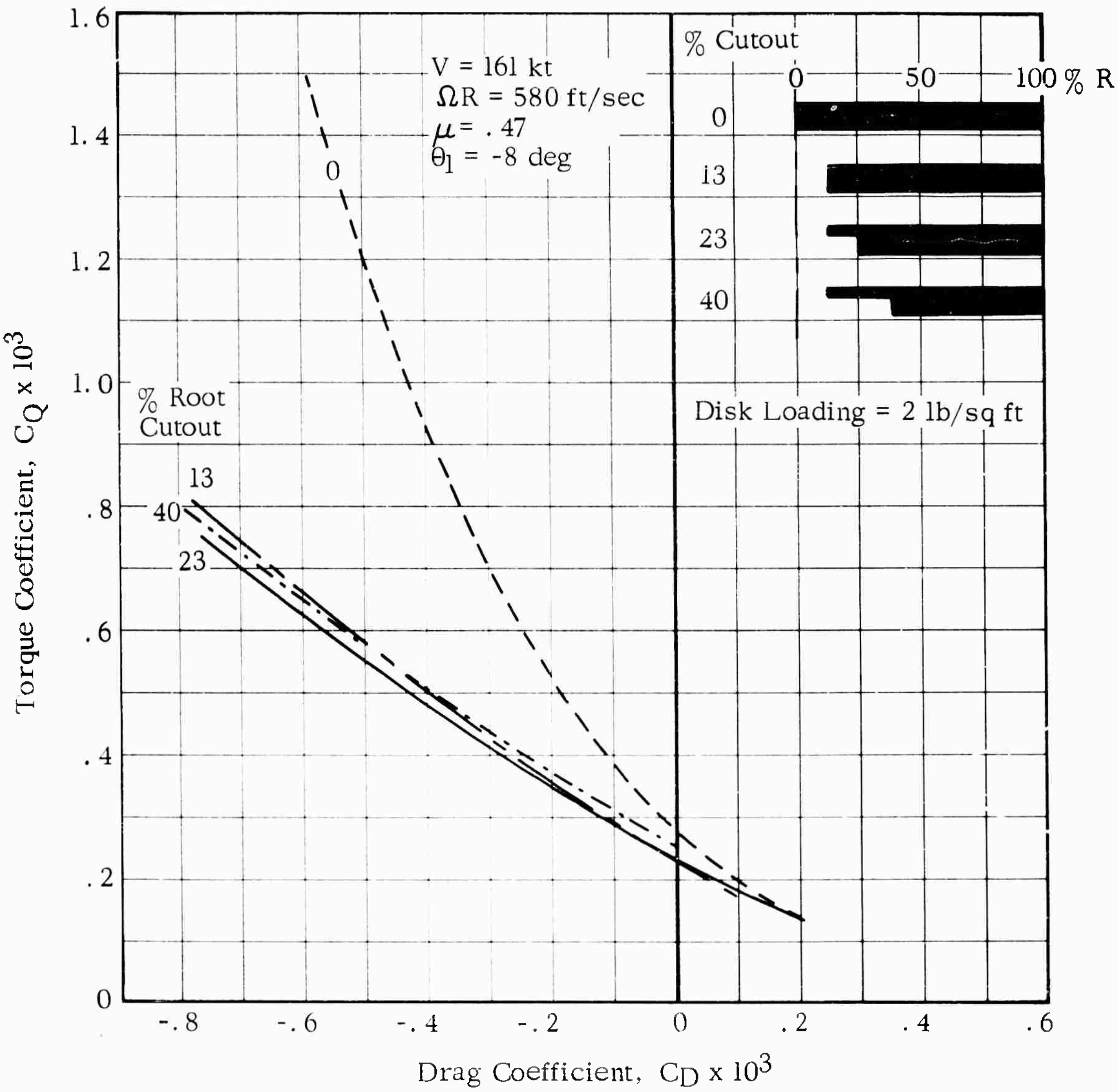
(c) C_L/σ = .04

FIG. 6. REPEATABILITY OF ROTOR PERFORMANCE DATA



(a) Without Spar

FIG. 7. EFFECT OF BLADE ROOT CUTOUT ON ROTOR PERFORMANCE



(b) With Spar

Figure 7. -Concluded

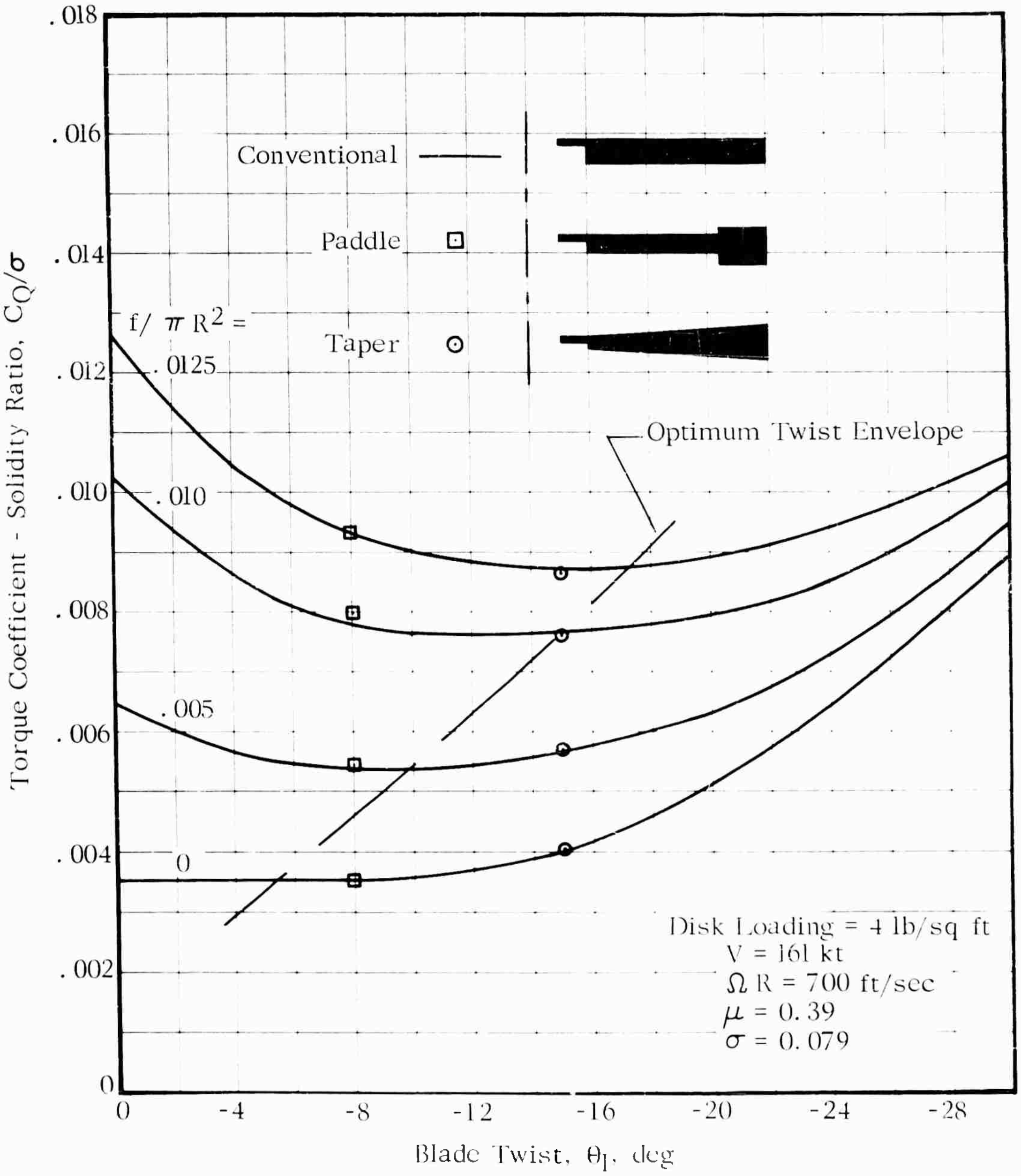


FIG. 8. THEORETICAL EFFECT OF BLADE TWIST AND PLANFORM ON TORQUE

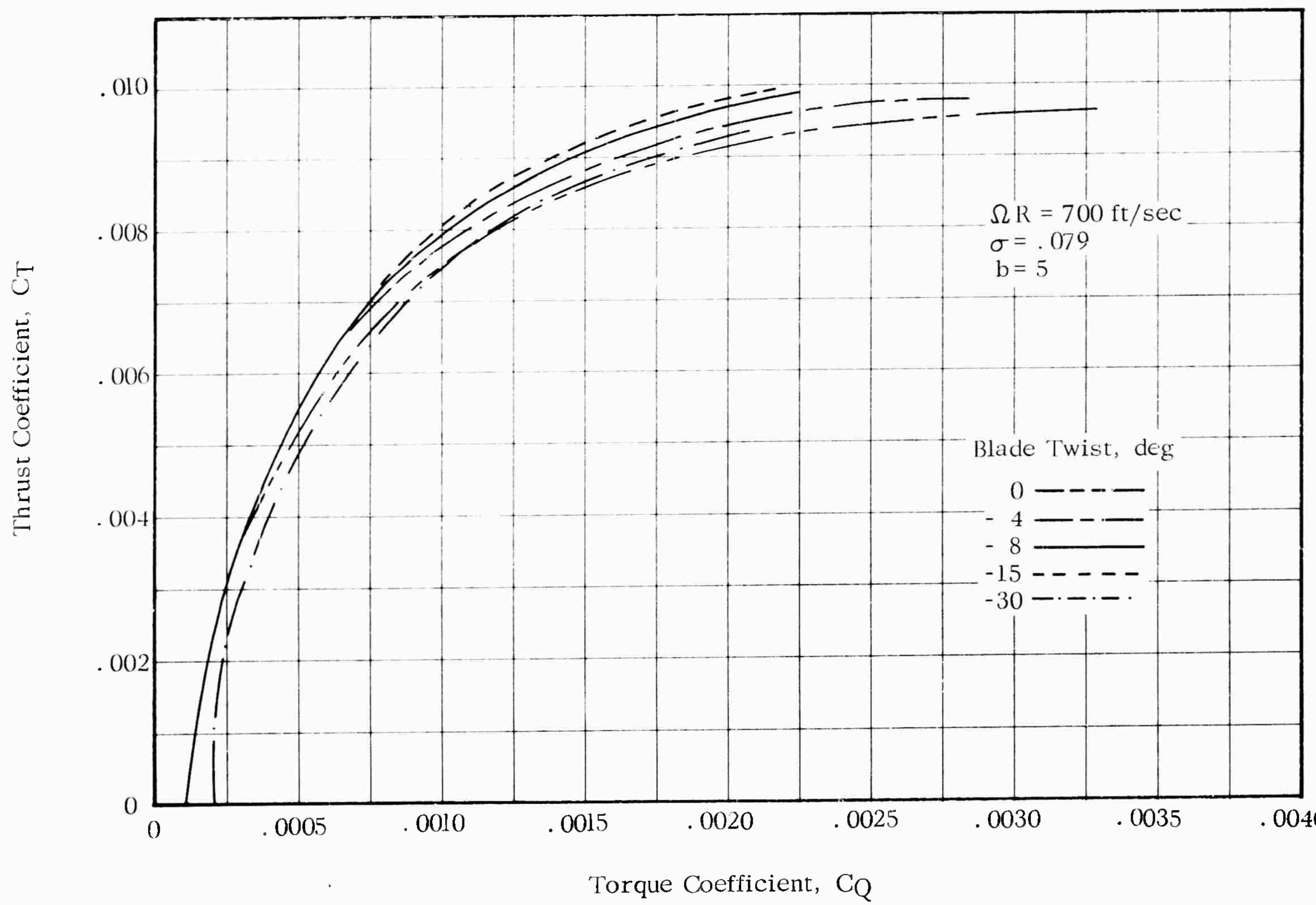


FIG. 9. THEORETICAL EFFECT OF BLADE TWIST ON HOVERING PERFORMANCE

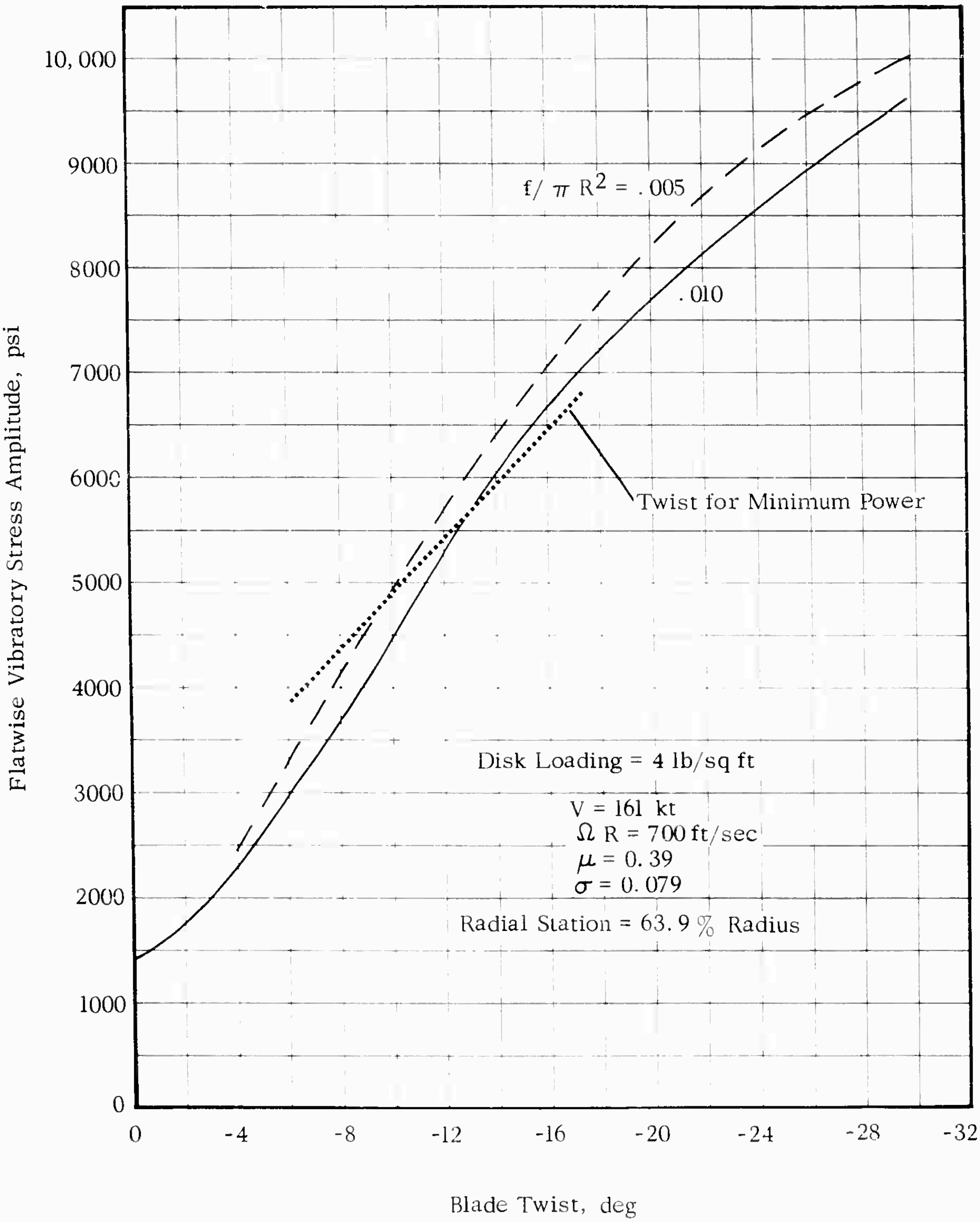


FIG. 10. THEORETICAL EFFECT OF BLADE TWIST ON VIBRATORY BLADE STRESS

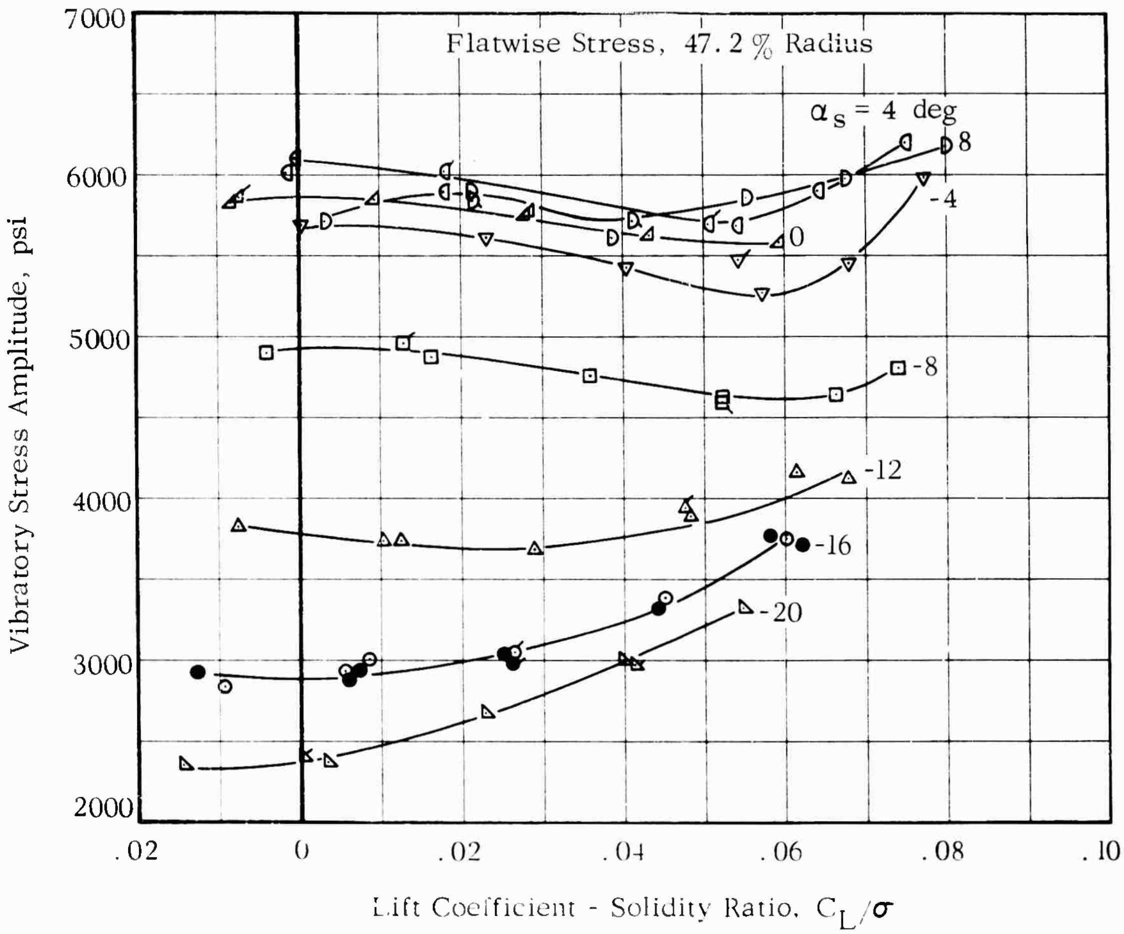
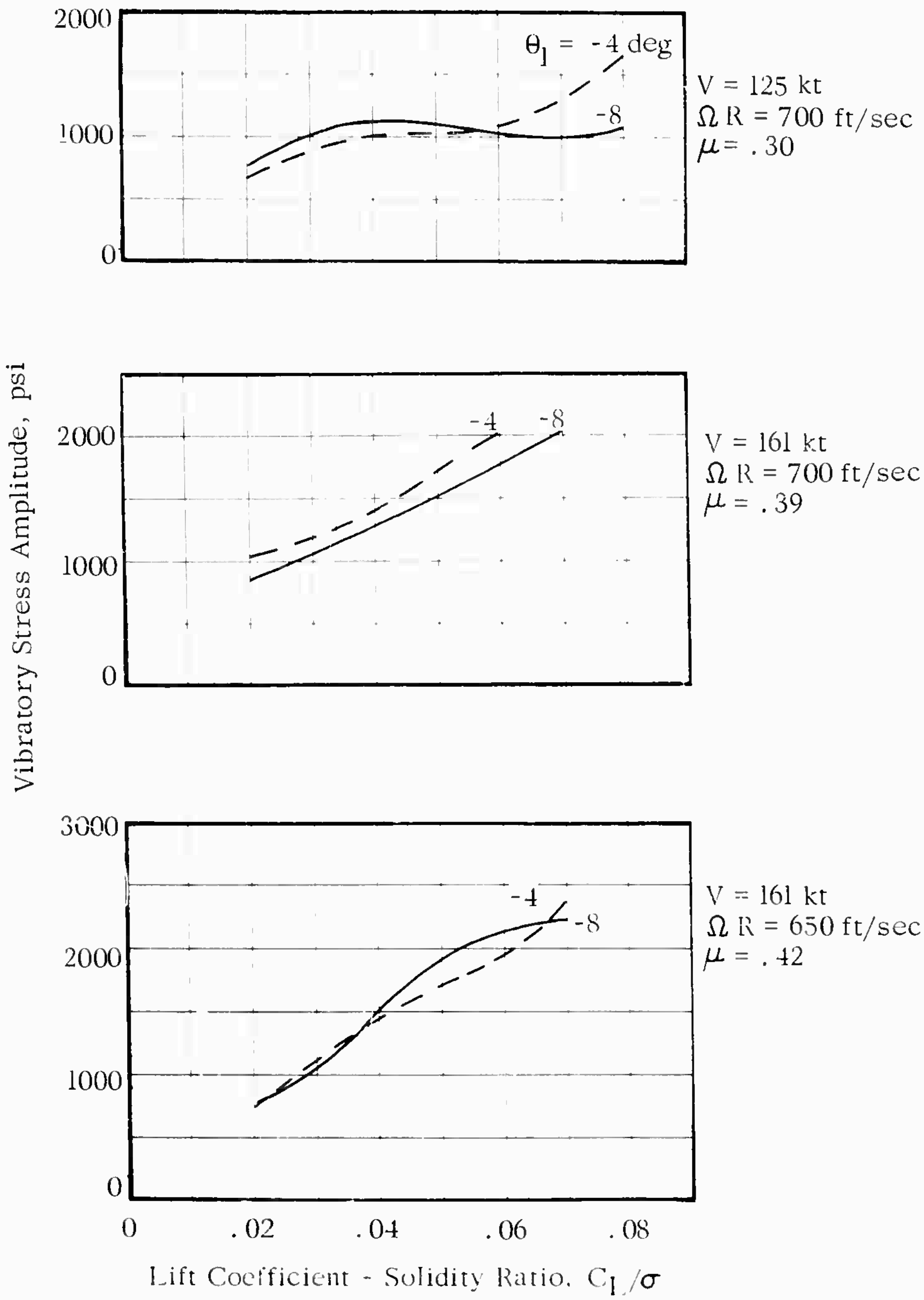


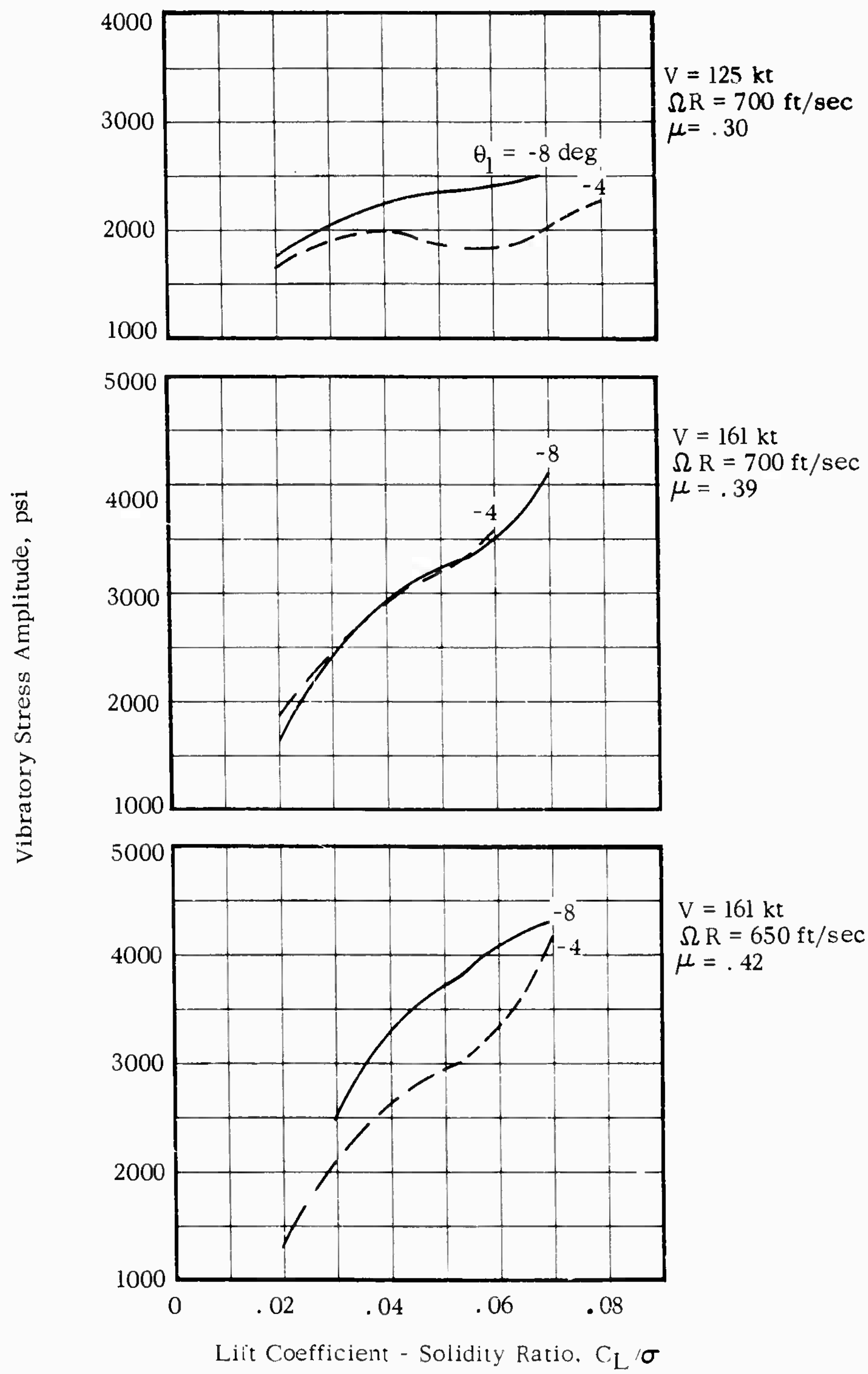
FIG. 11. TYPICAL EXPERIMENTAL BASIC VIBRATORY STRESS DATA

V = 161 kt ΩR = 700 ft/sec μ = .39 θ_1 = -8 deg



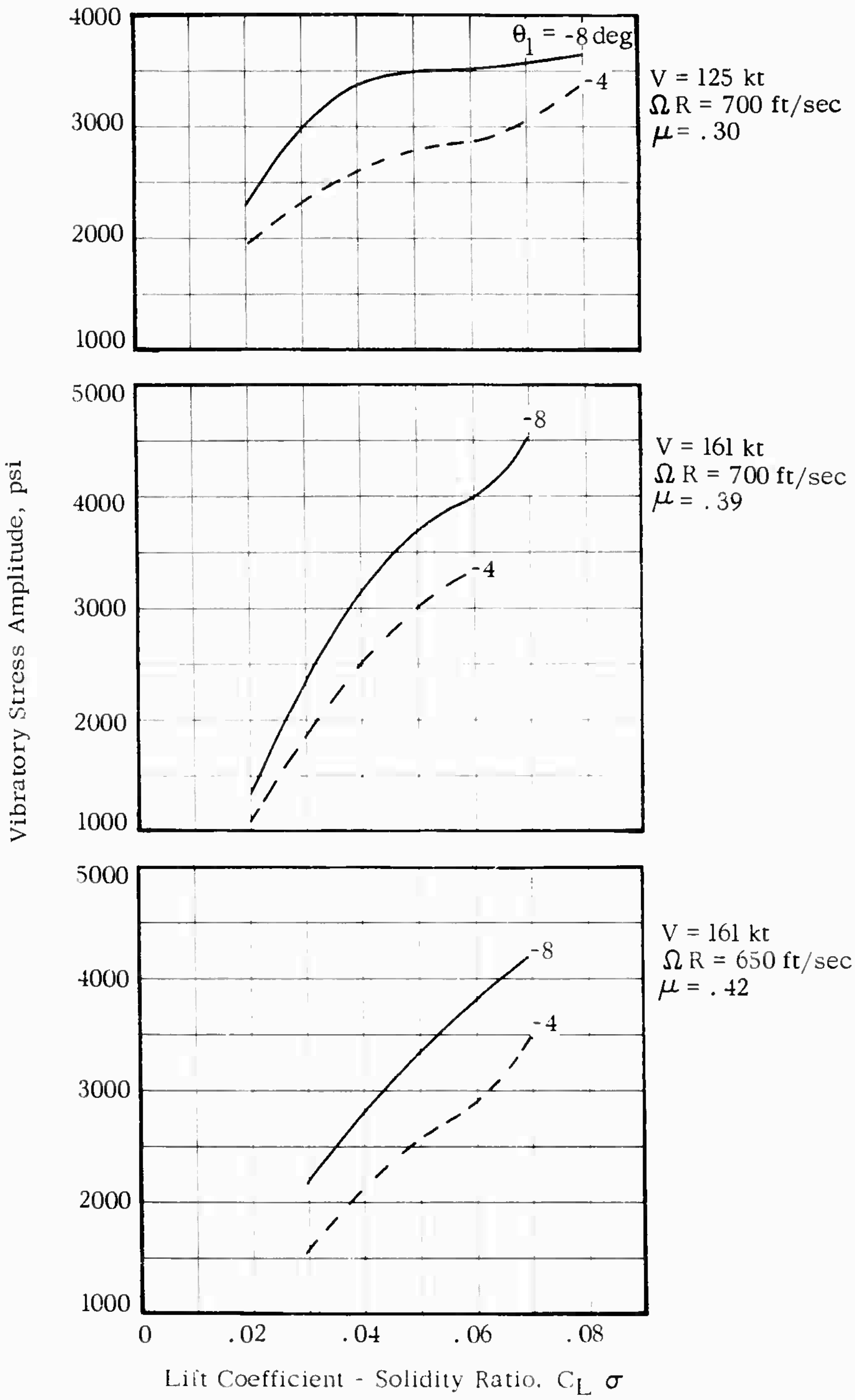
(a) Flatwise Stress, 21.0% Radius

FIG. 12. EXPERIMENTAL EFFECT OF BLADE TWIST AND LIFT ON FLATWISE STRESS, $f/\pi R^2 = 0.005$



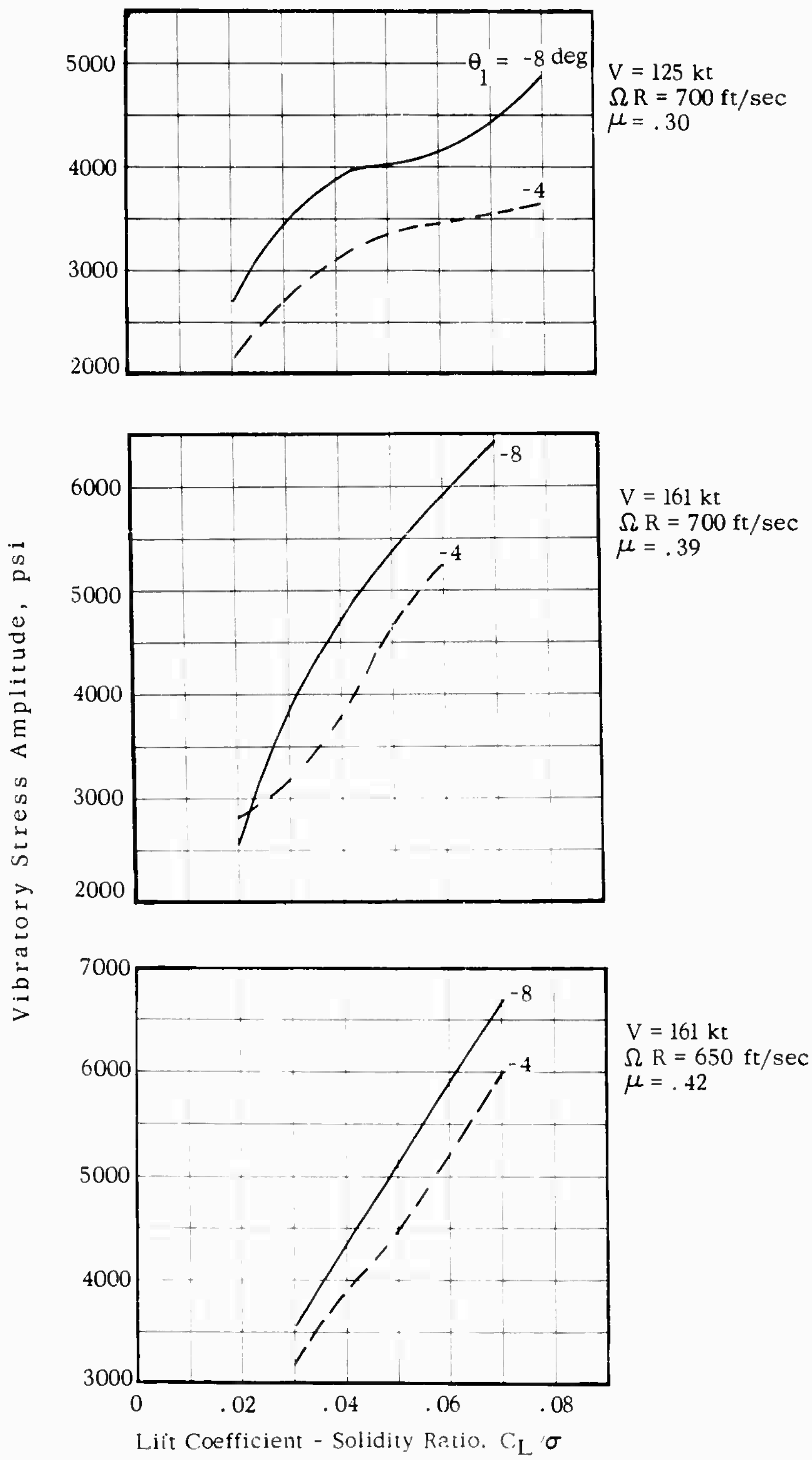
(b) Flatwise Stress, 33.4% Radius

Figure 12. -Continued



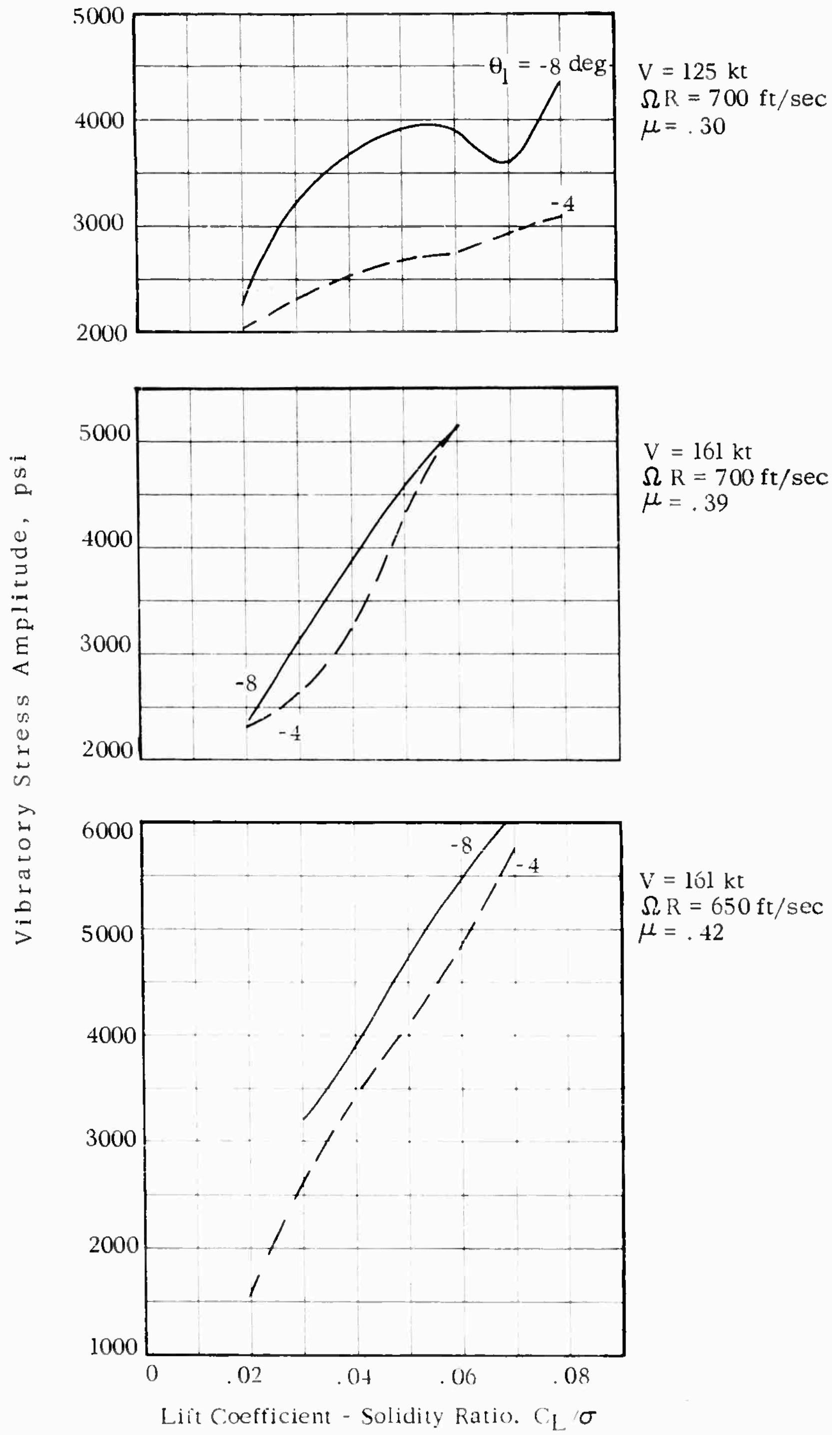
(c) Flatwise Stress, 47.2 % Radius

Figure 12. -Continued



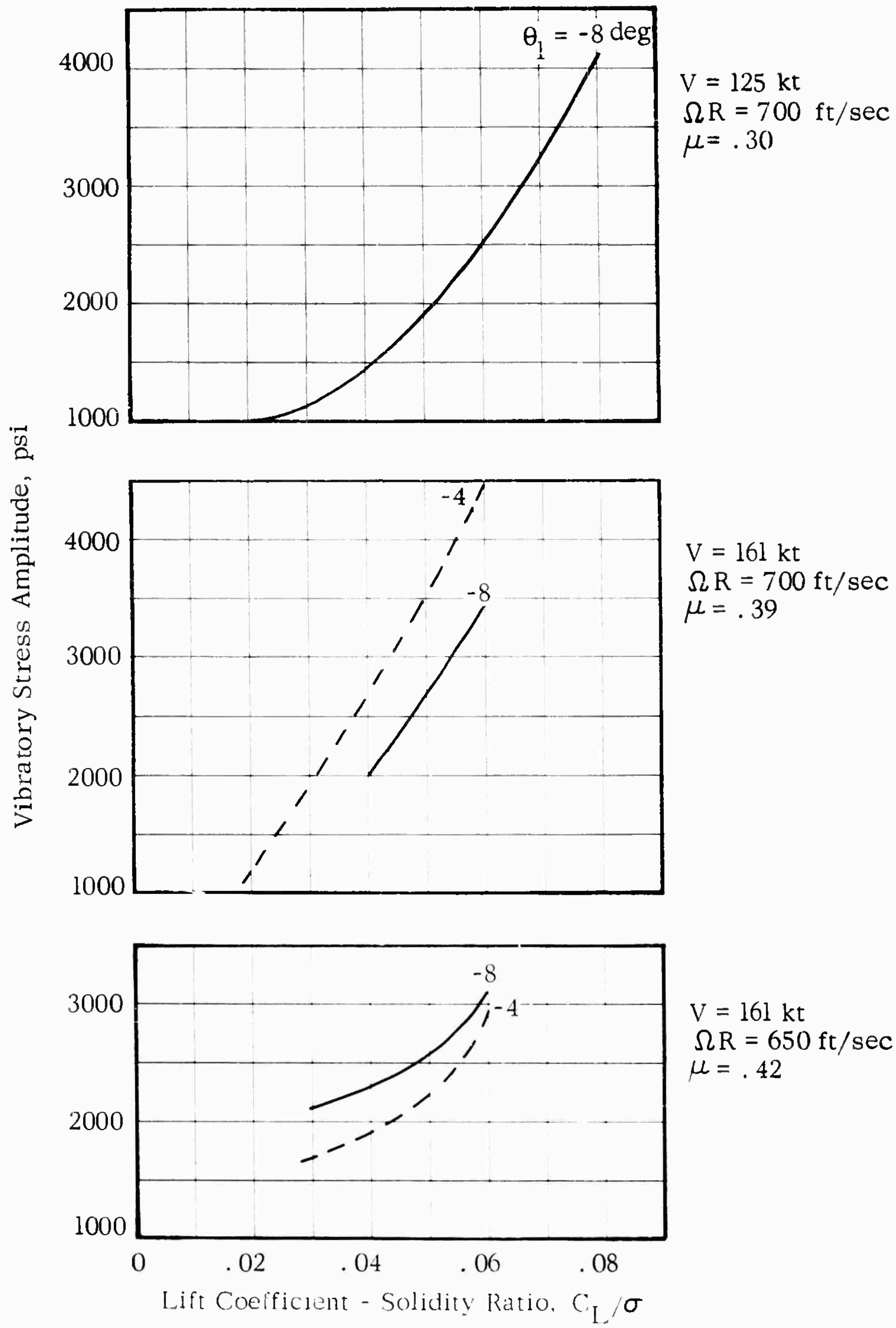
(d) Flatwise Stress, 63.9 % Radius

Figure 12. -Continued



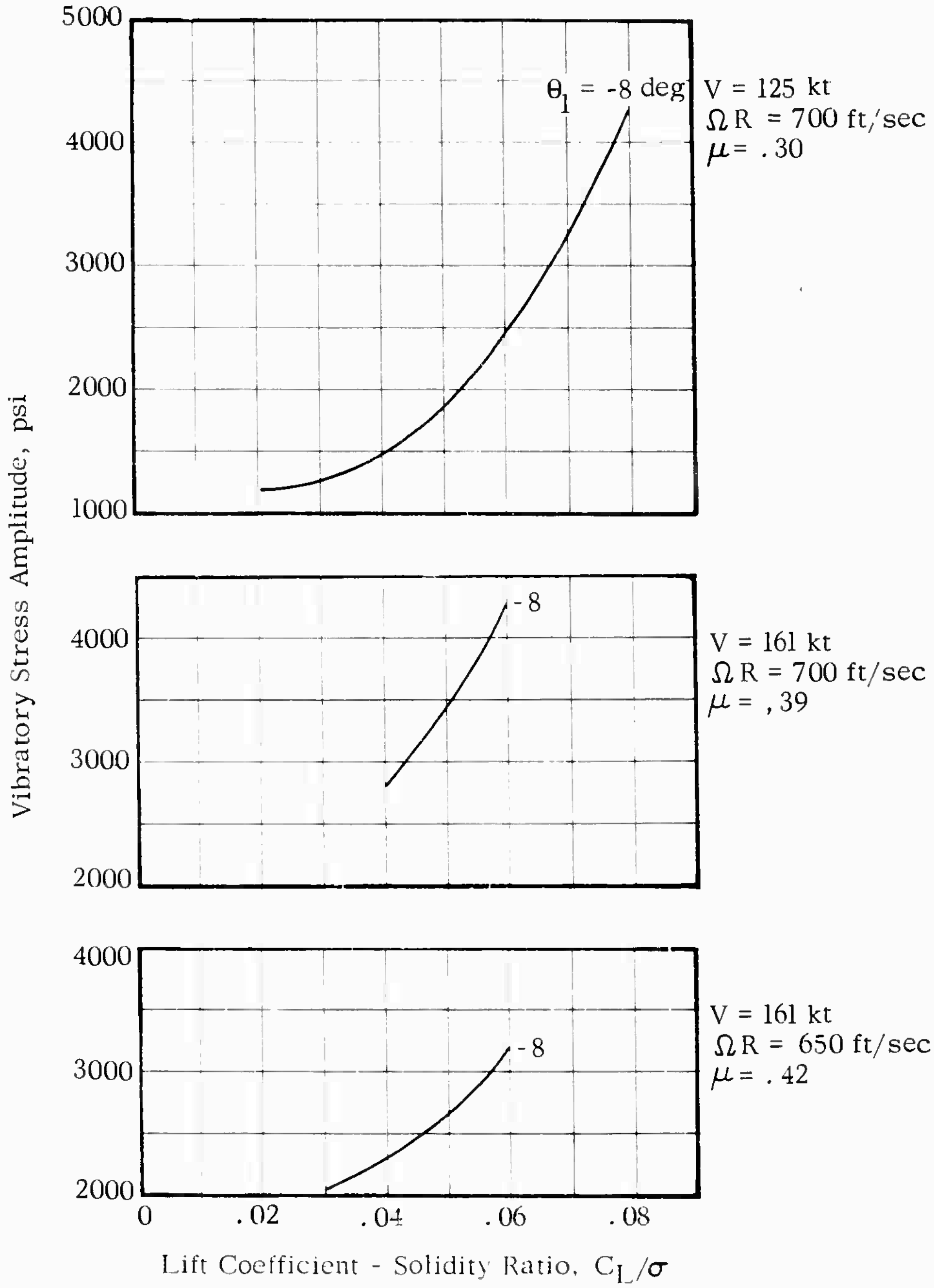
(e) Flatwise Stress, 80.5% Radius

Figure 12. -Concluded



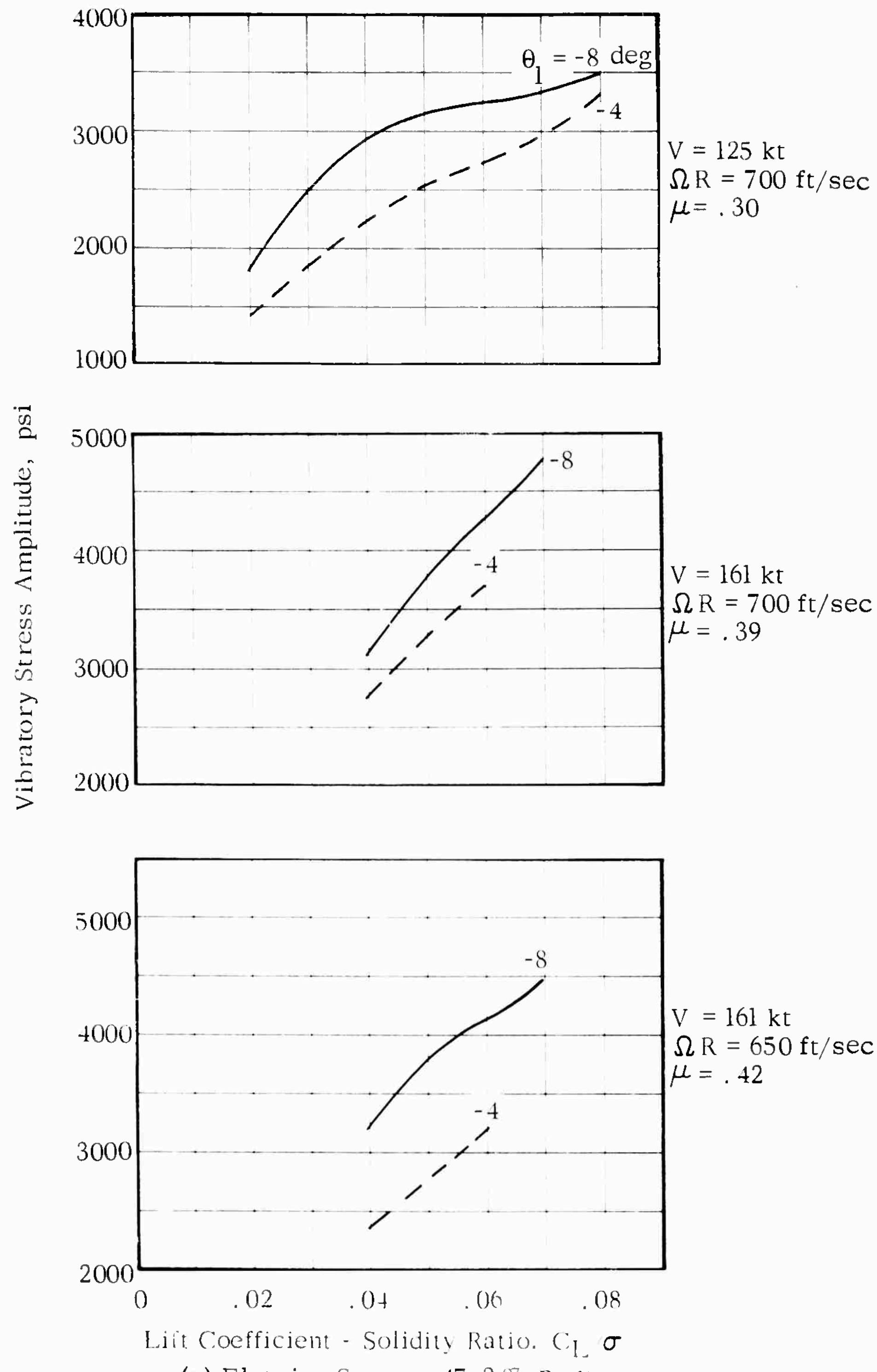
(a) Chordwise Stress, 33.4% Radius

FIG. 13. EXPERIMENTAL EFFECT OF BLADE TWIST AND LIFT ON CHORDWISE STRESS, $f/\pi R^2 = 0.005$



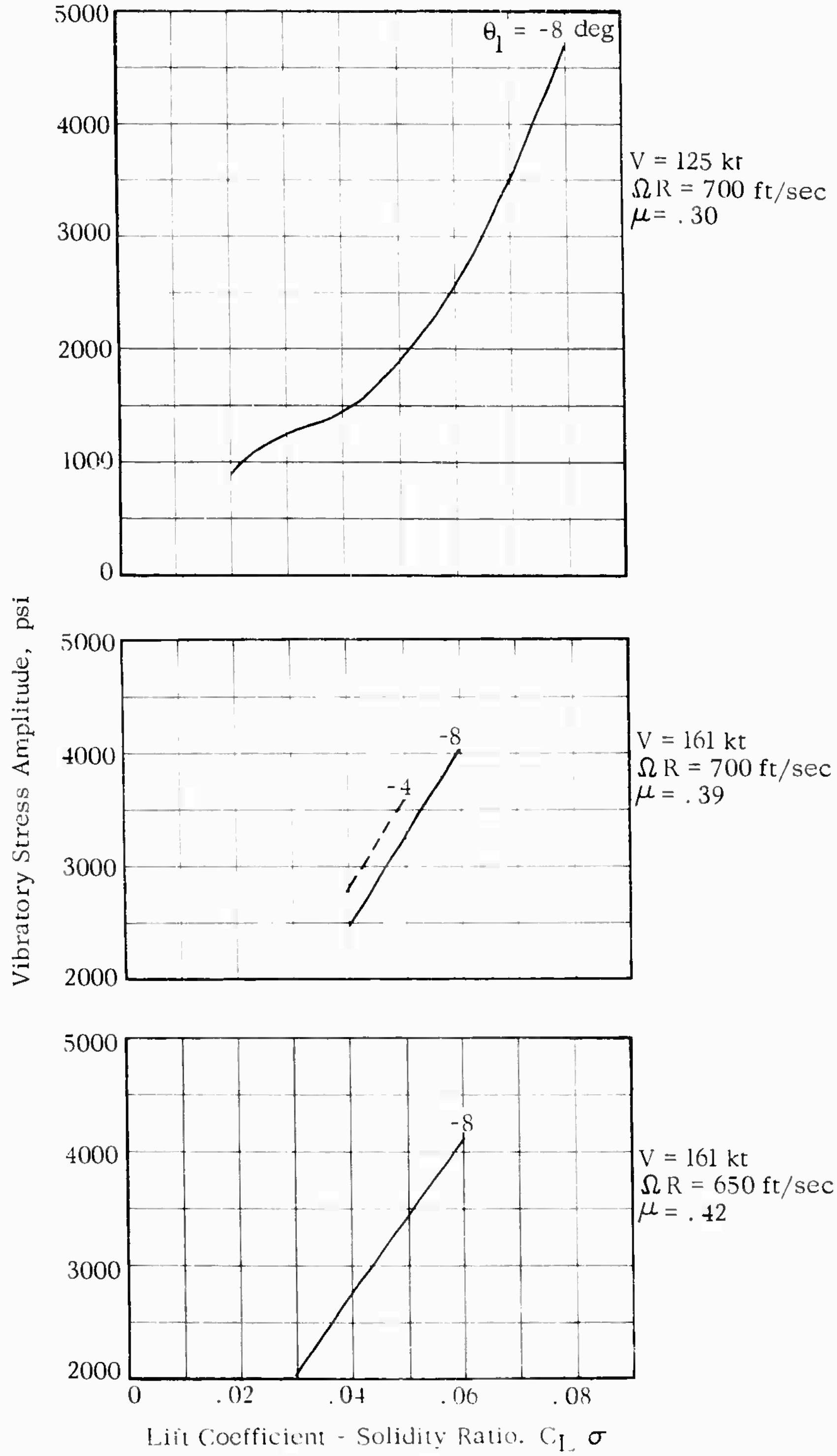
(b) Chordwise Stress, 47.2% Radius

Figure 13.- Concluded



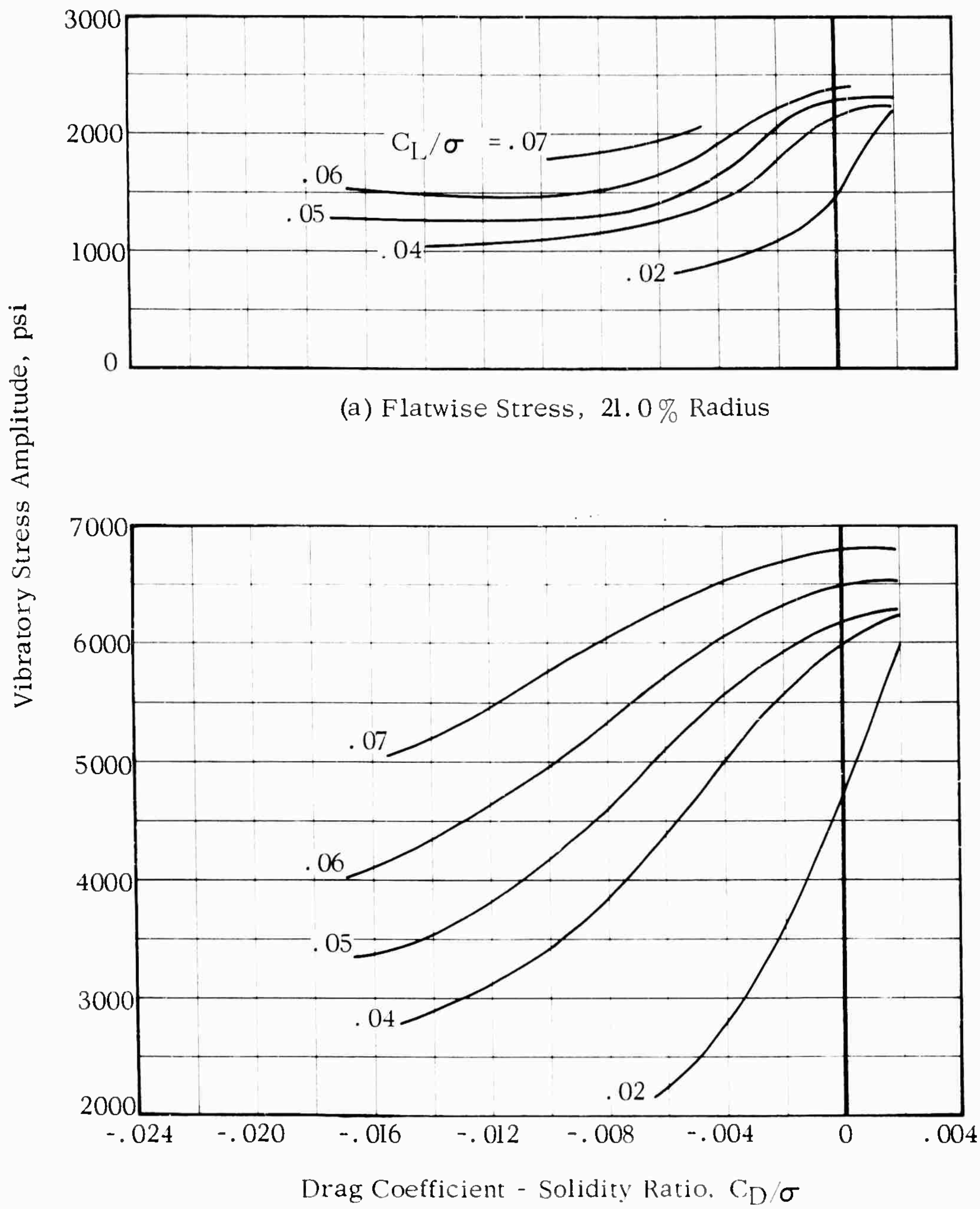
(a) Flatwise Stress, 47.2 % Radius

FIG. 14. EXPERIMENTAL EFFECT OF BLADE TWIST AND LIFT ON FLATWISE AND CHORDWISE STRESS, $f/\pi R^2 = 0.010$



(b) Chordwise Stress, 47.2% Radius

Figure 14. -Concluded

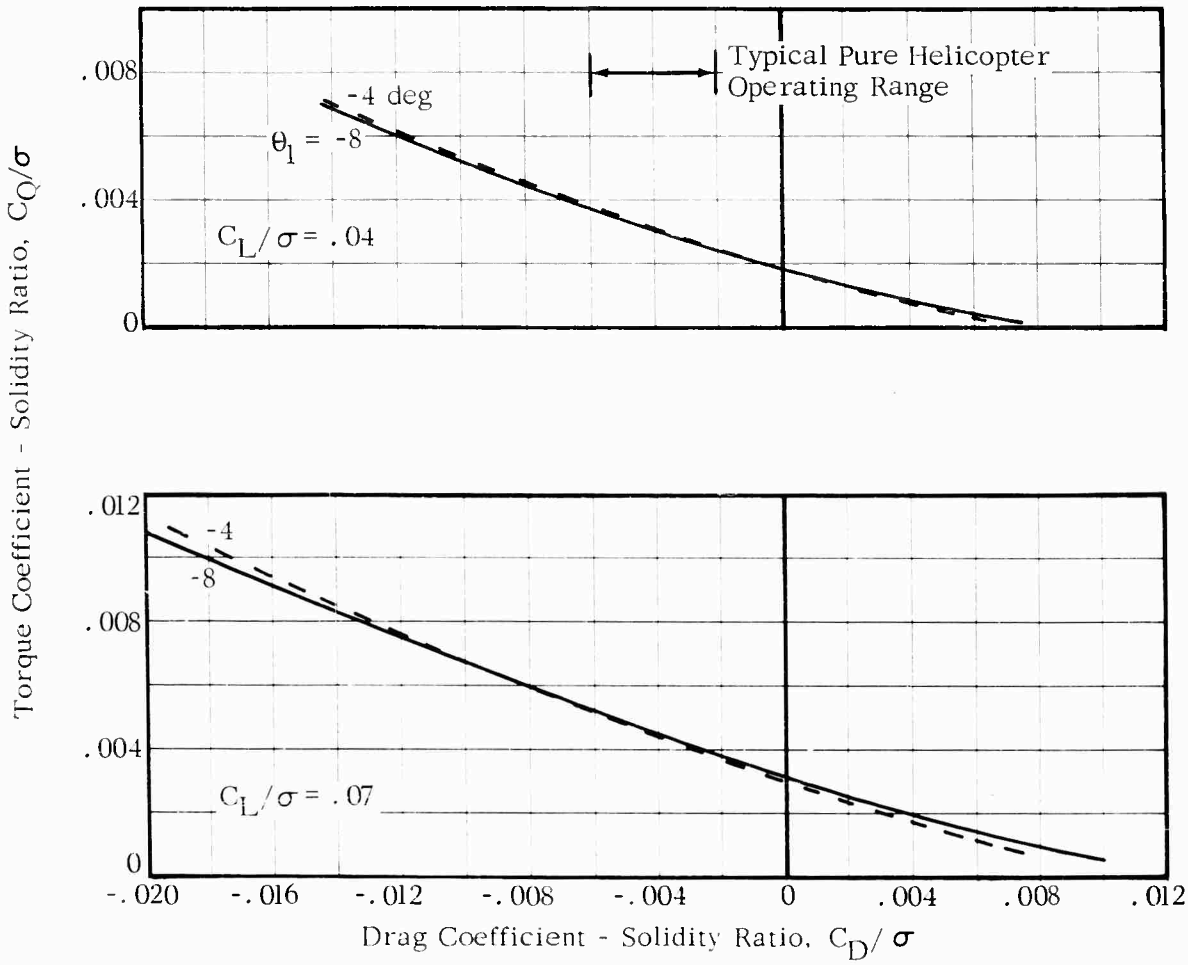


(a) Flatwise Stress, 21.0 % Radius

(b) Flatwise Stress, 63.9 % Radius

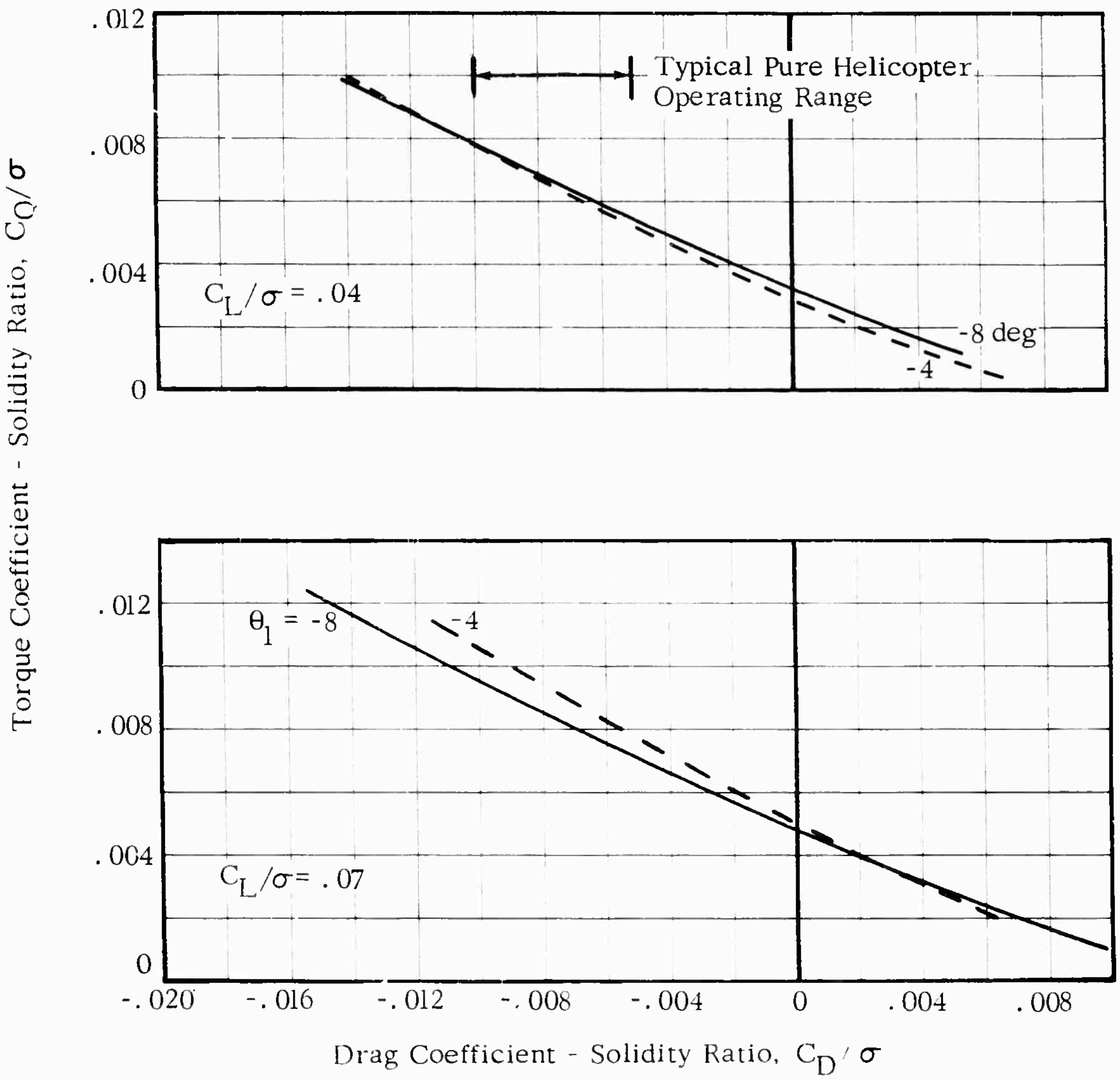
FIG. 15. EFFECT OF ROTOR LIFT AND PROPULSIVE FORCE ON VIBRATORY BLADE STRESS

V = 161 kt ΩR = 700 ft/sec μ = .39 θ_1 = -8 deg



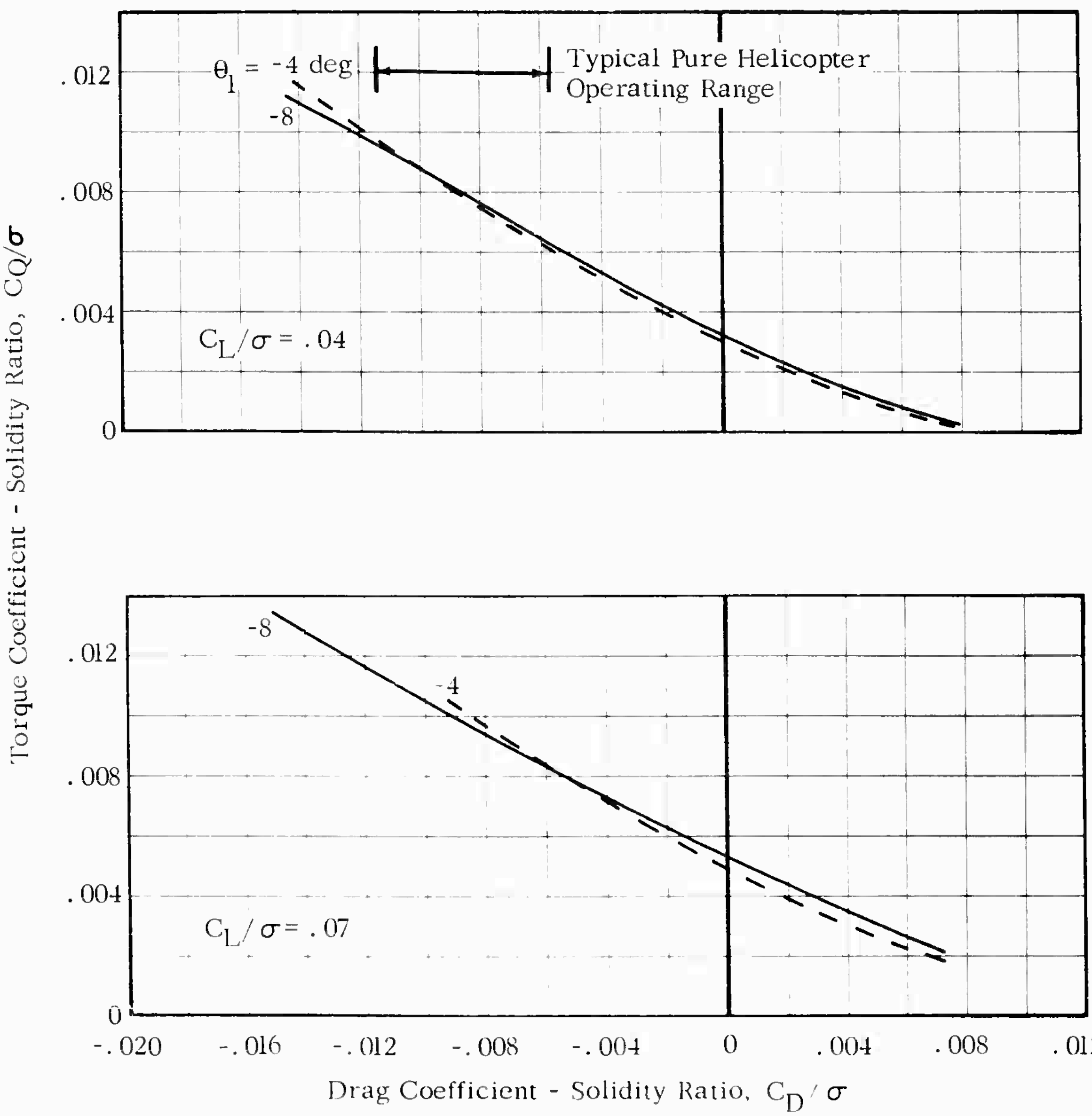
(a) V = 125 kt, ΩR = 700 ft/sec, μ = .30

FIG. 16. EXPERIMENTAL EFFECT OF BLADE TWIST ON ROTOR PERFORMANCE



(b) V = 161 kt, ΩR = 700 ft/sec, μ= .39

Figure 16. -Continued

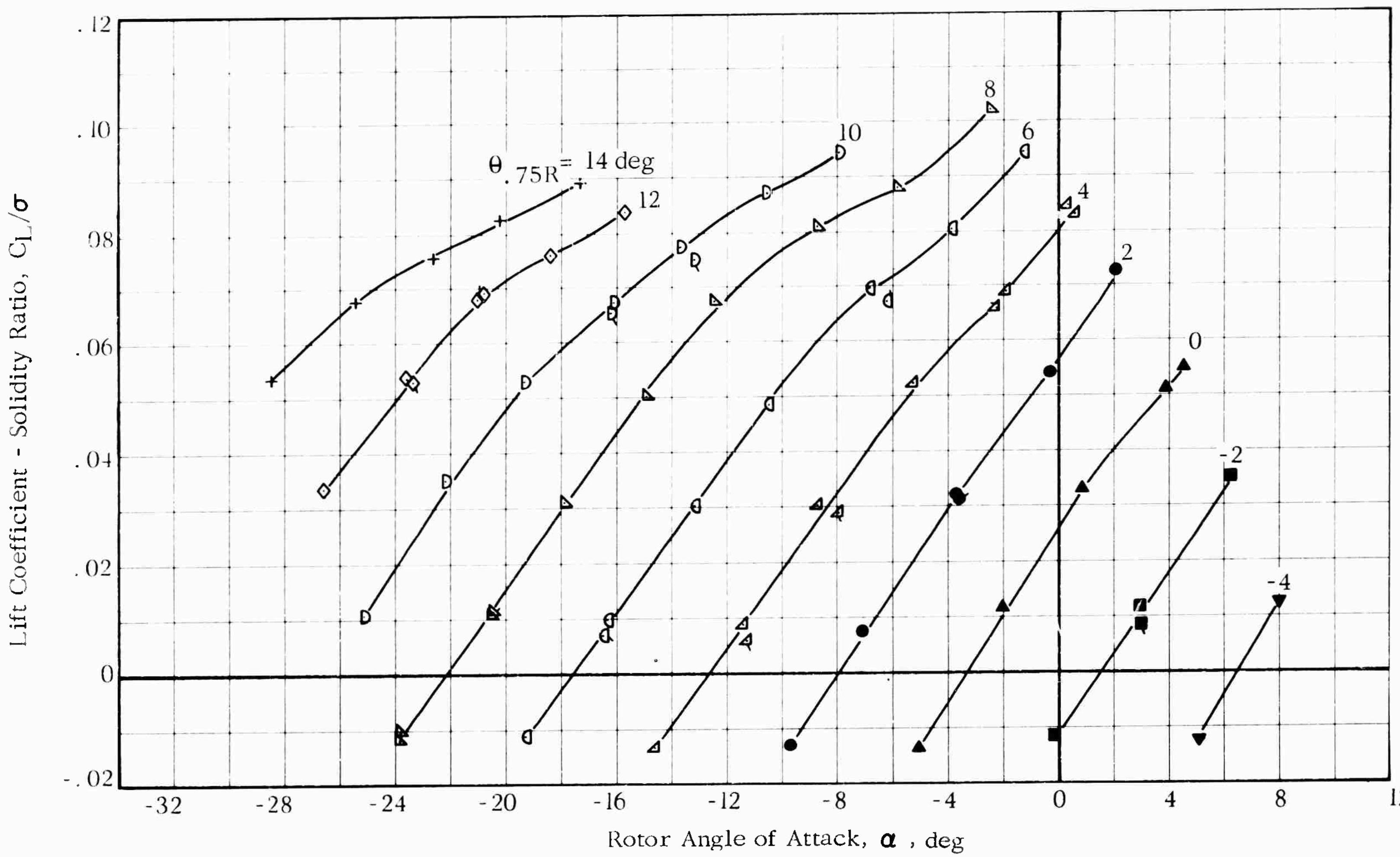


(c) V = 161 kt, ΩR = 650 ft/sec, μ = .42

Figure 16. -Concluded

APPENDIX I

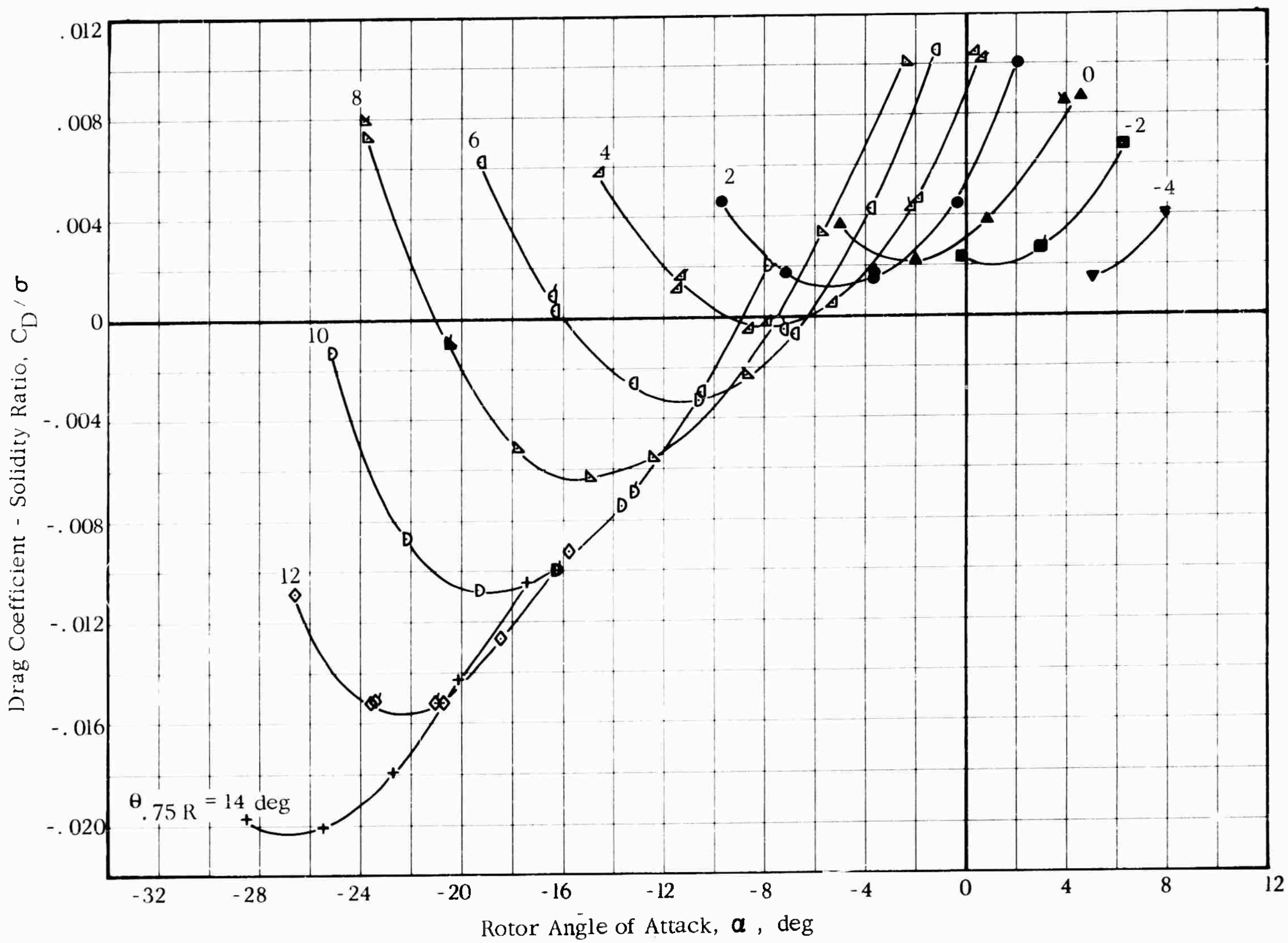
BASIC ROTOR PERFORMANCE



(a) C_L/σ vs α

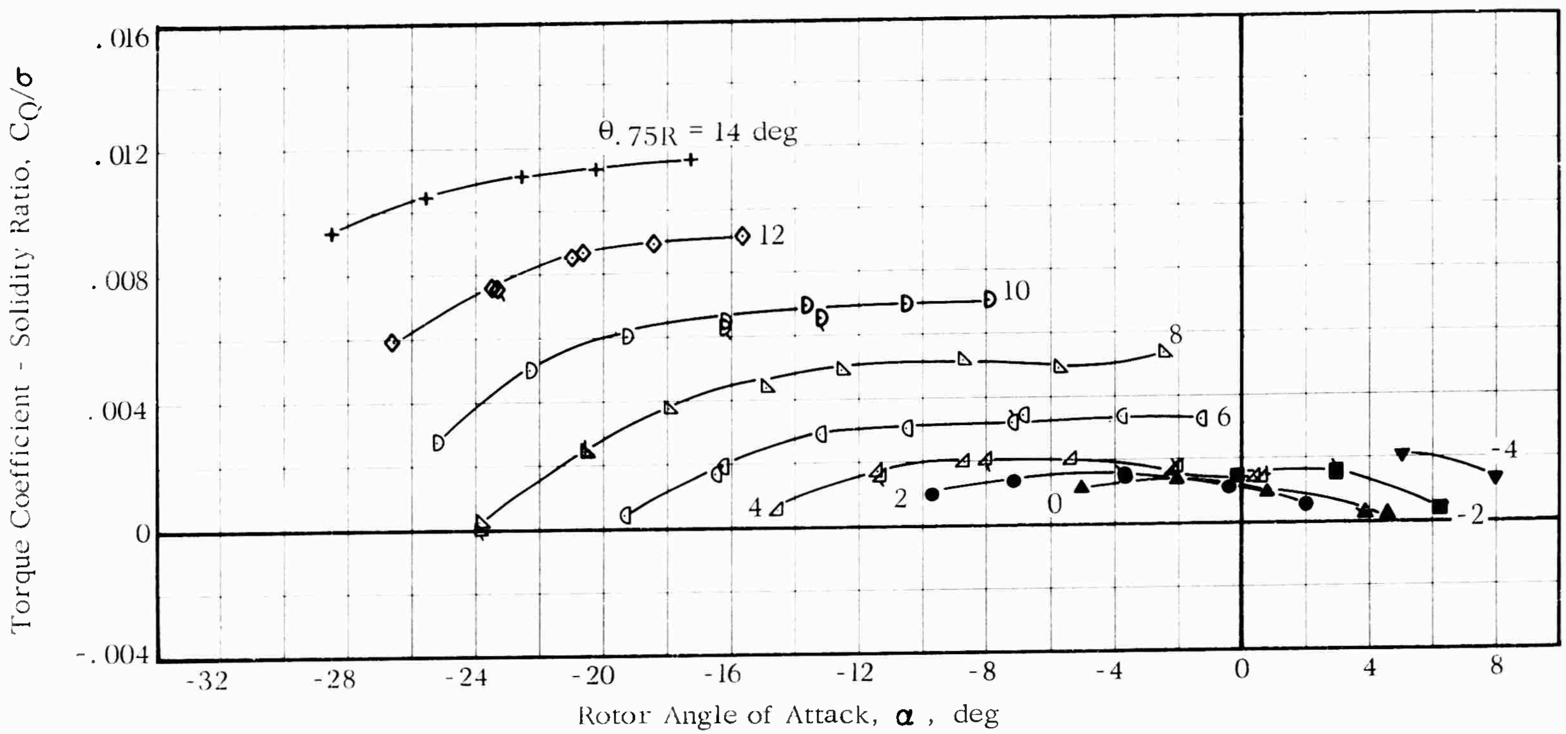
FIG. 17. EXPERIMENTAL ROTOR PERFORMANCE

V = 125 kt $\qquad \Omega R$ = 700 ft/sec $\qquad \mu = .30 \qquad \theta_1 = -8$ deg



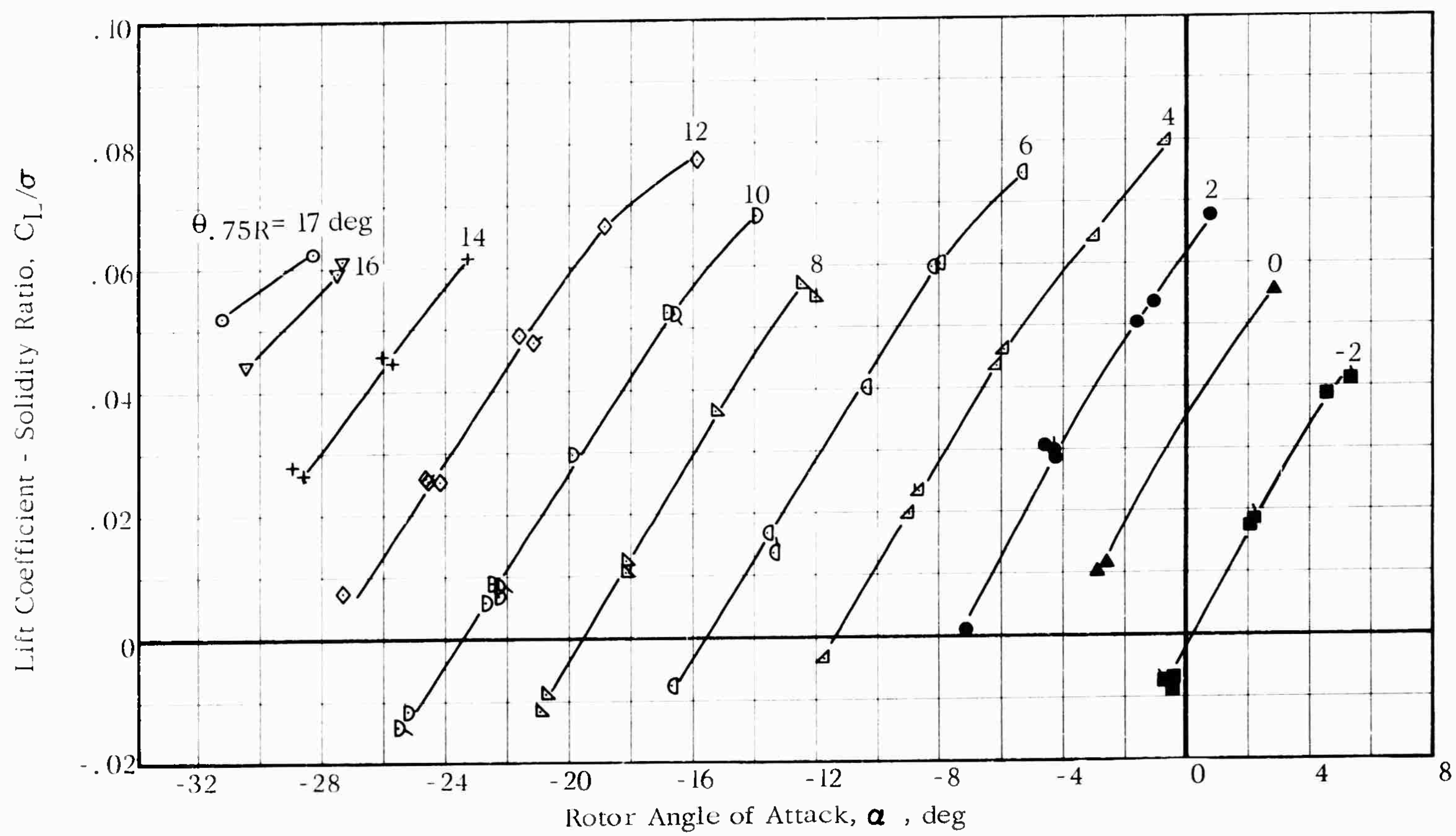
(b) C_D / σ vs α

Figure 17. -Continued



(c) C_Q/σ vs α

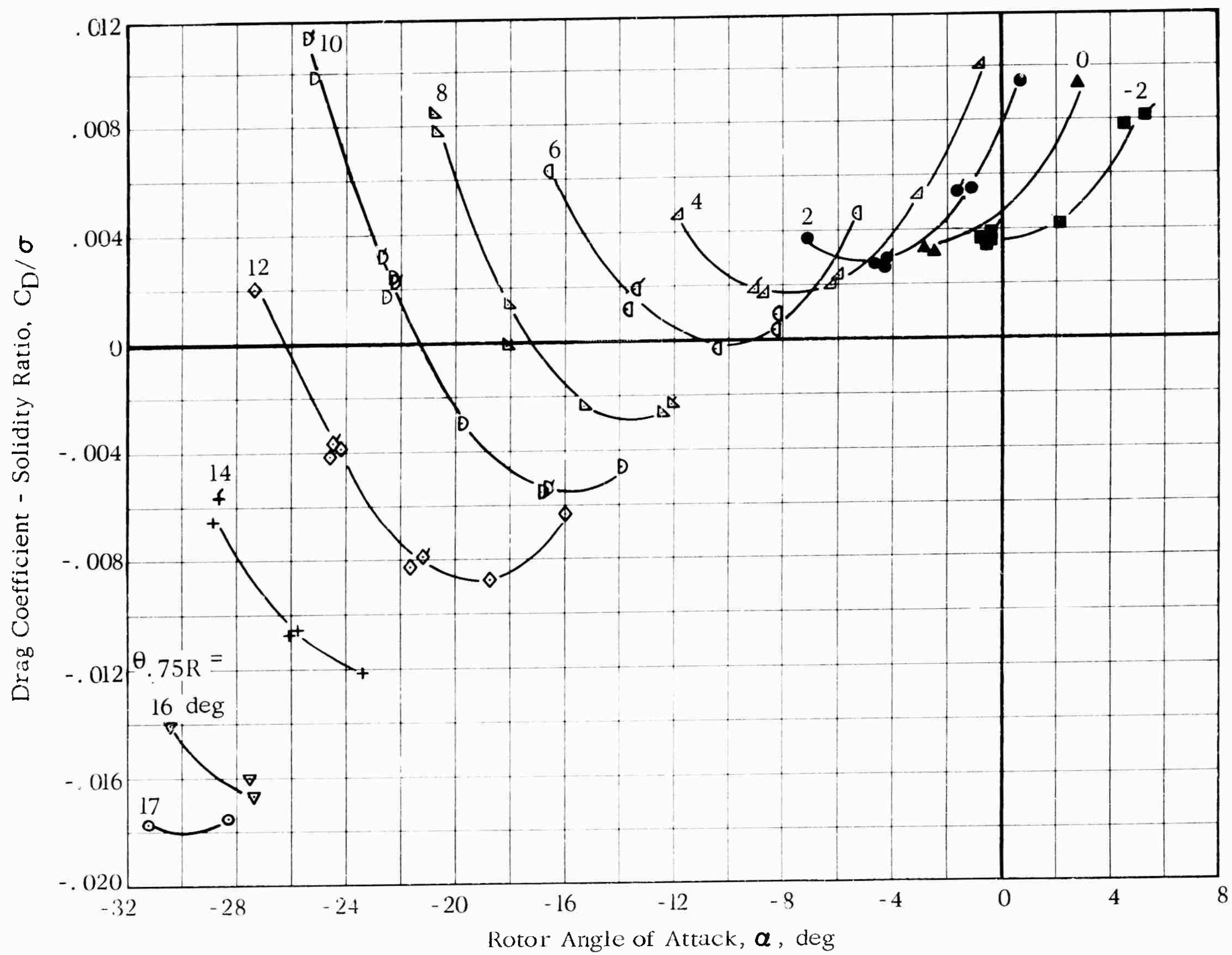
Figure 17. -Concluded



(a) C_L/σ vs α

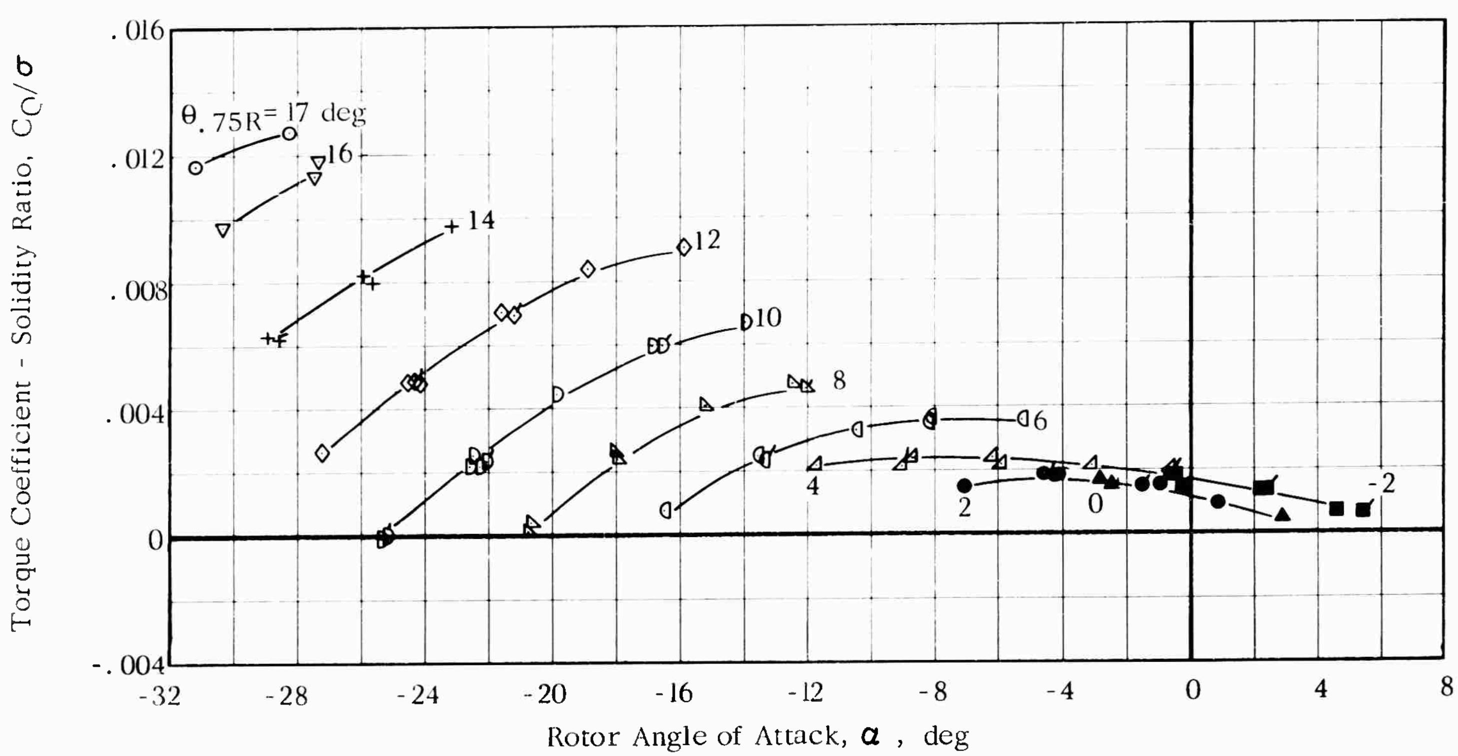
FIG. 18. EXPERIMENTAL ROTOR PERFORMANCE

V = 161 kt ΩR = 700 ft/sec μ = .39 θ_1 = -8 deg



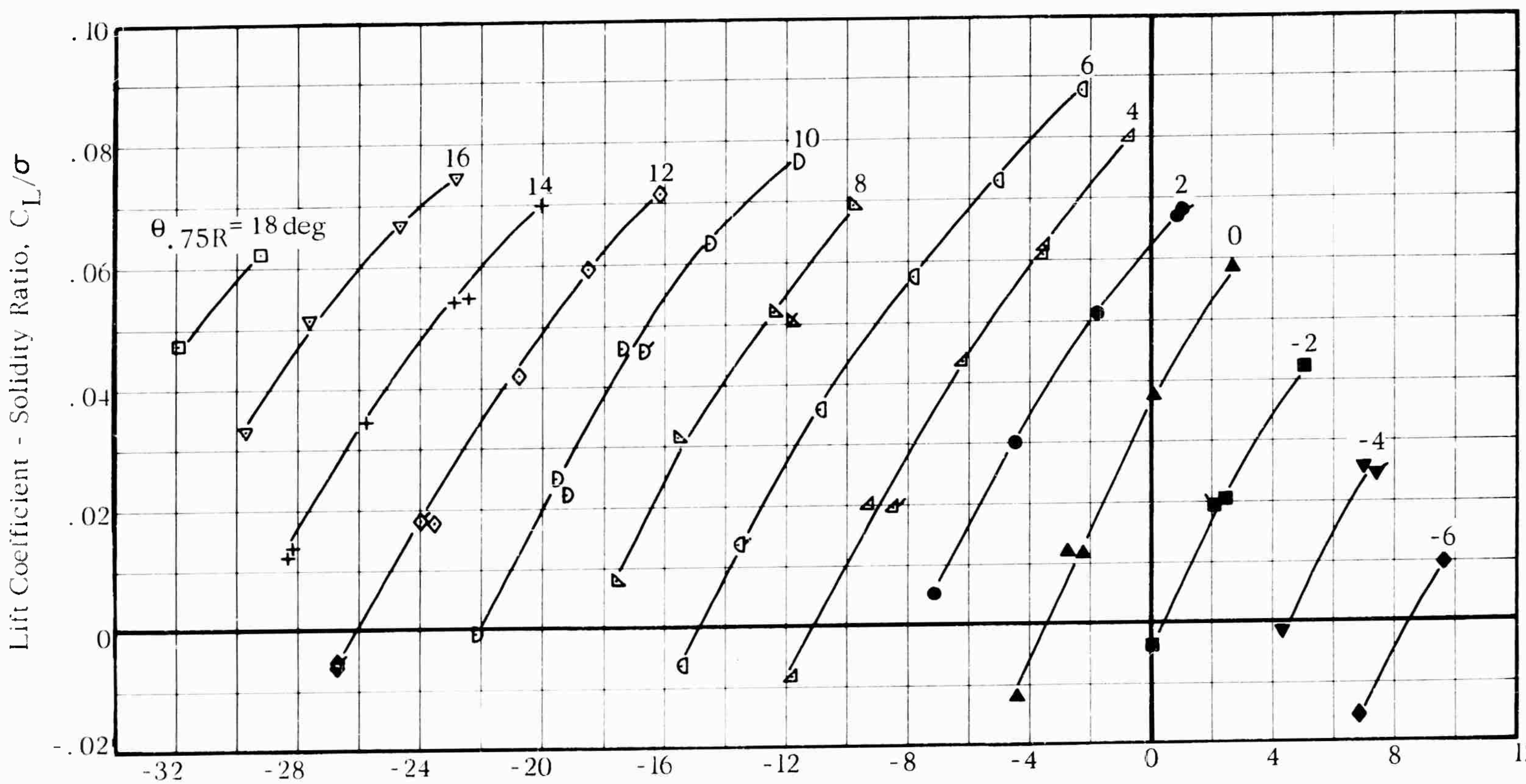
(b) C_D/σ vs α

Figure 18. -Continued



(c) C_Q/σ vs α

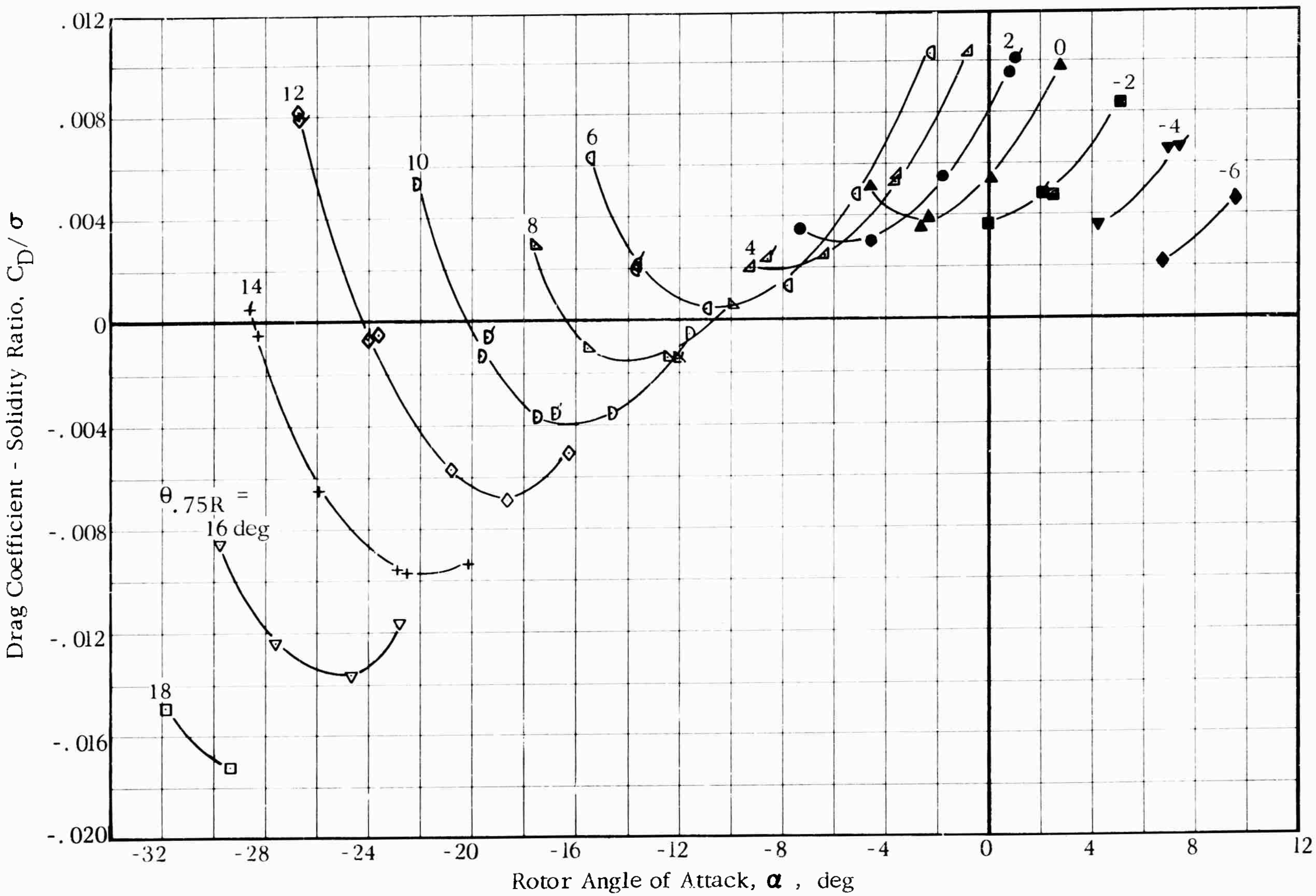
Figure 18. -Concluded



(a) C_L/σ vs α

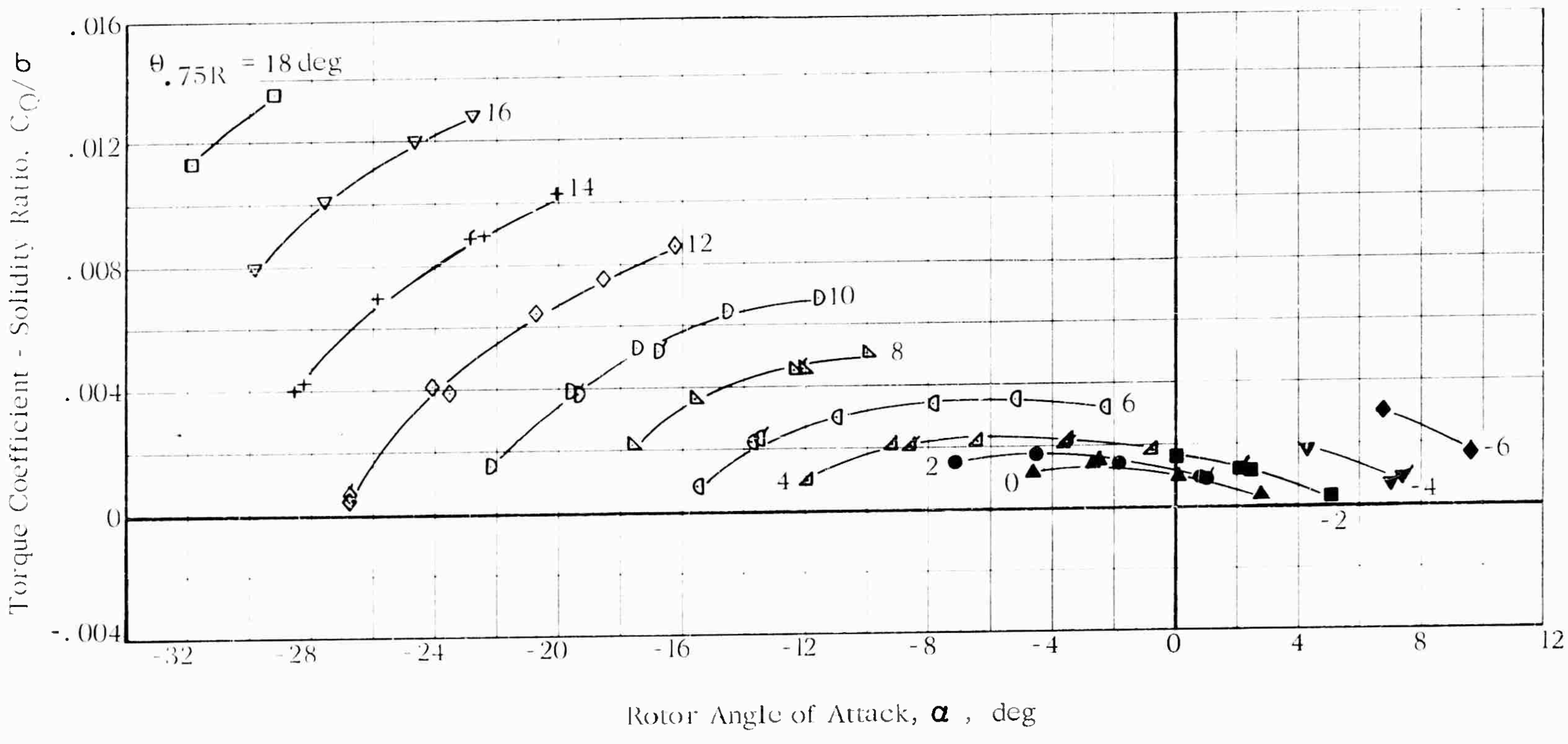
FIG. 19. EXPERIMENTAL ROTOR PERFORMANCE

V = 161 kt ΩR = 650 ft/sec μ = .42 θ_1 = -8 deg



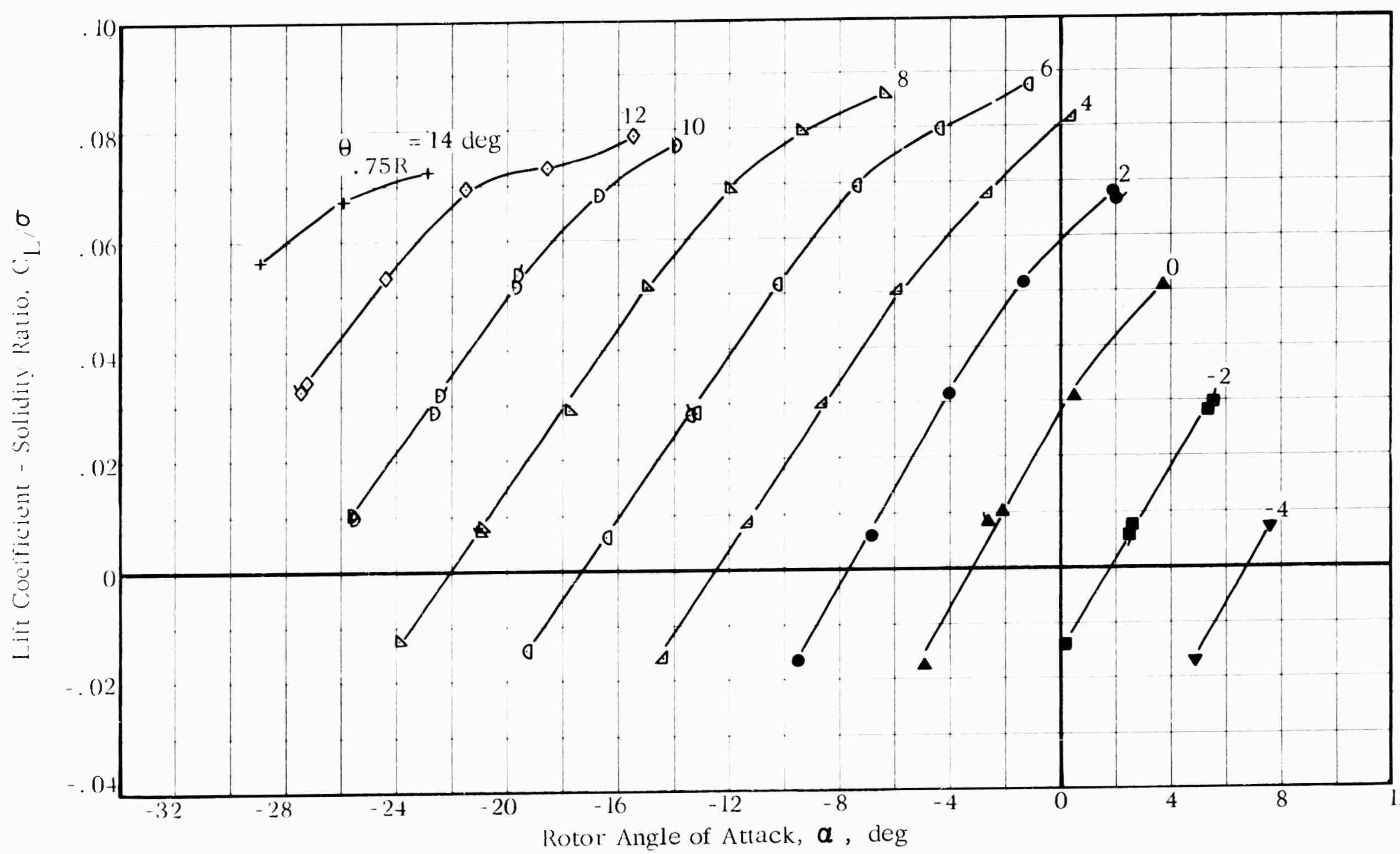
(b) C_D/σ vs α

Figure 19. - Continued



(c) C_Q/σ vs α

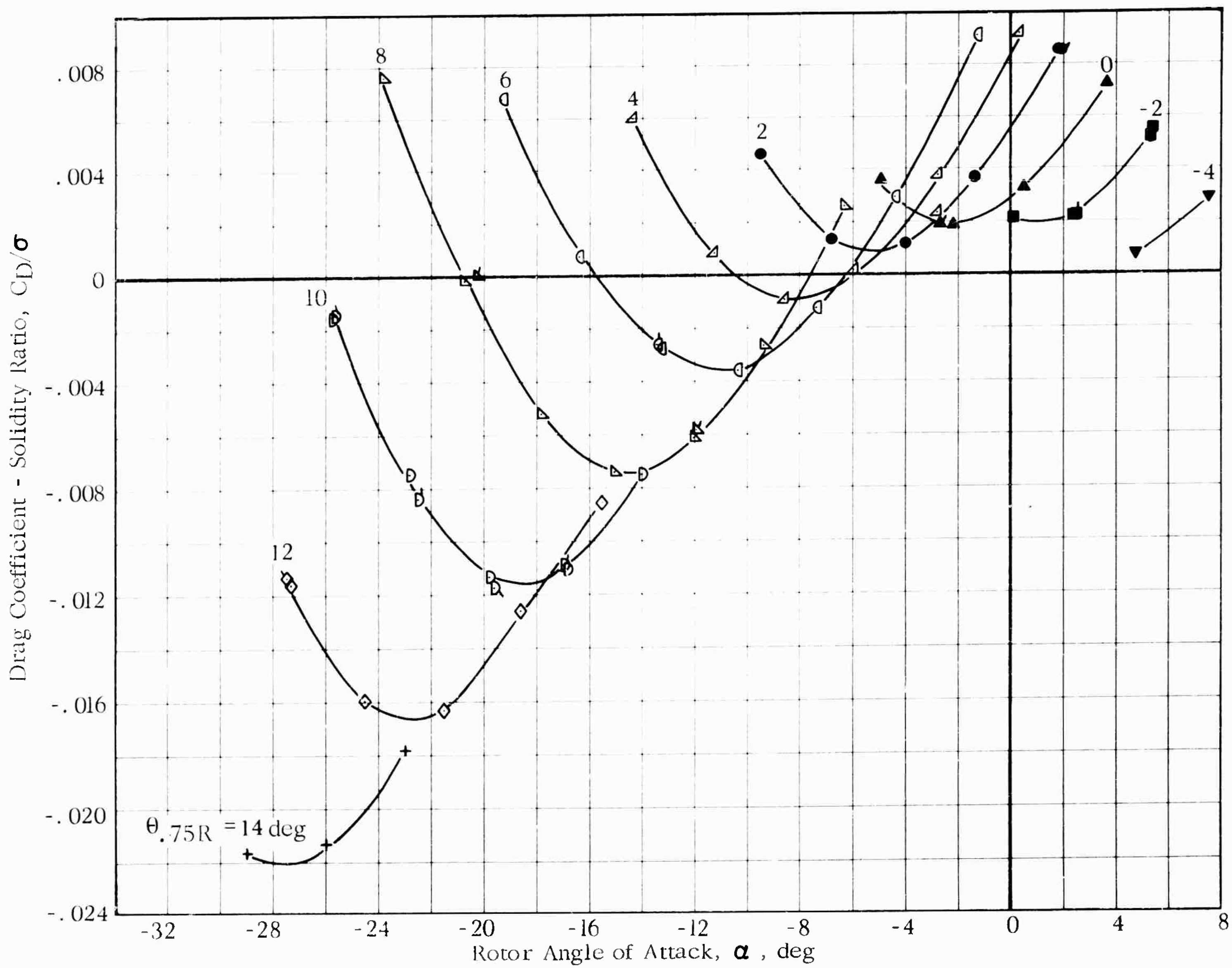
Figure 19. -Concluded



(a) C_L/σ vs α

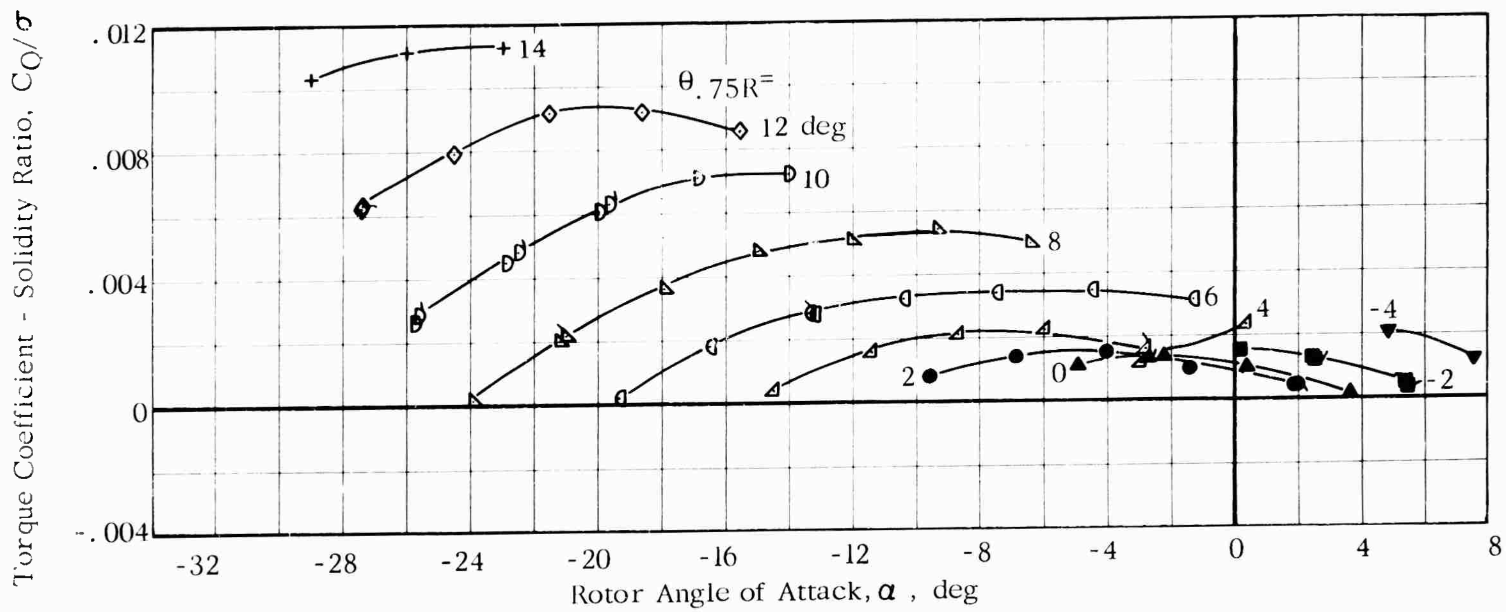
FIG. 20. EXPERIMENTAL ROTOR PERFORMANCE

V = 125 kt $\quad \Omega R$ = 700 ft/sec $\quad \mu = .30 \quad \theta_1 = -4$ deg



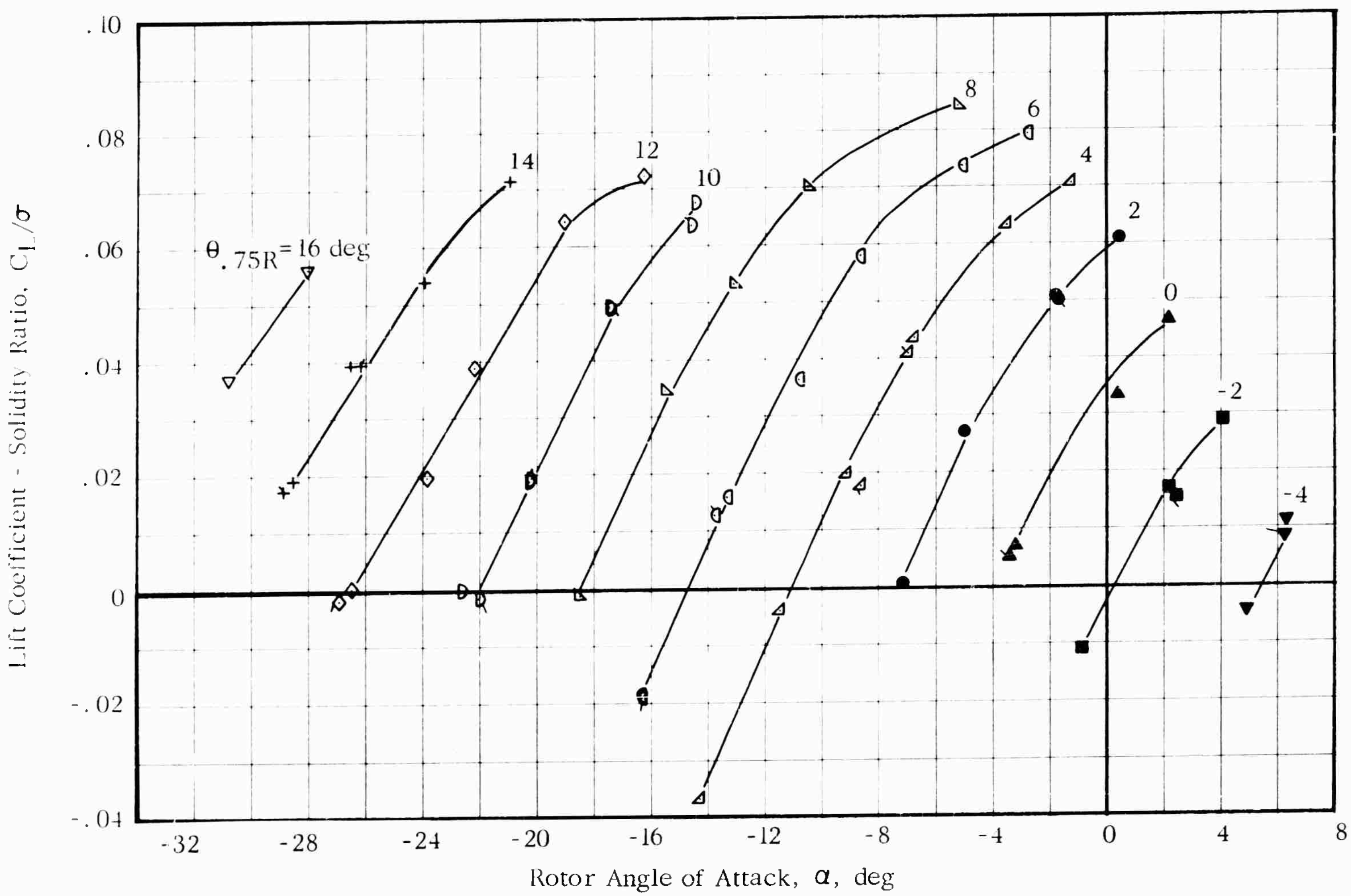
(b) C_D/σ vs α

Figure 20. -Continued



(c) C_Q/σ vs α

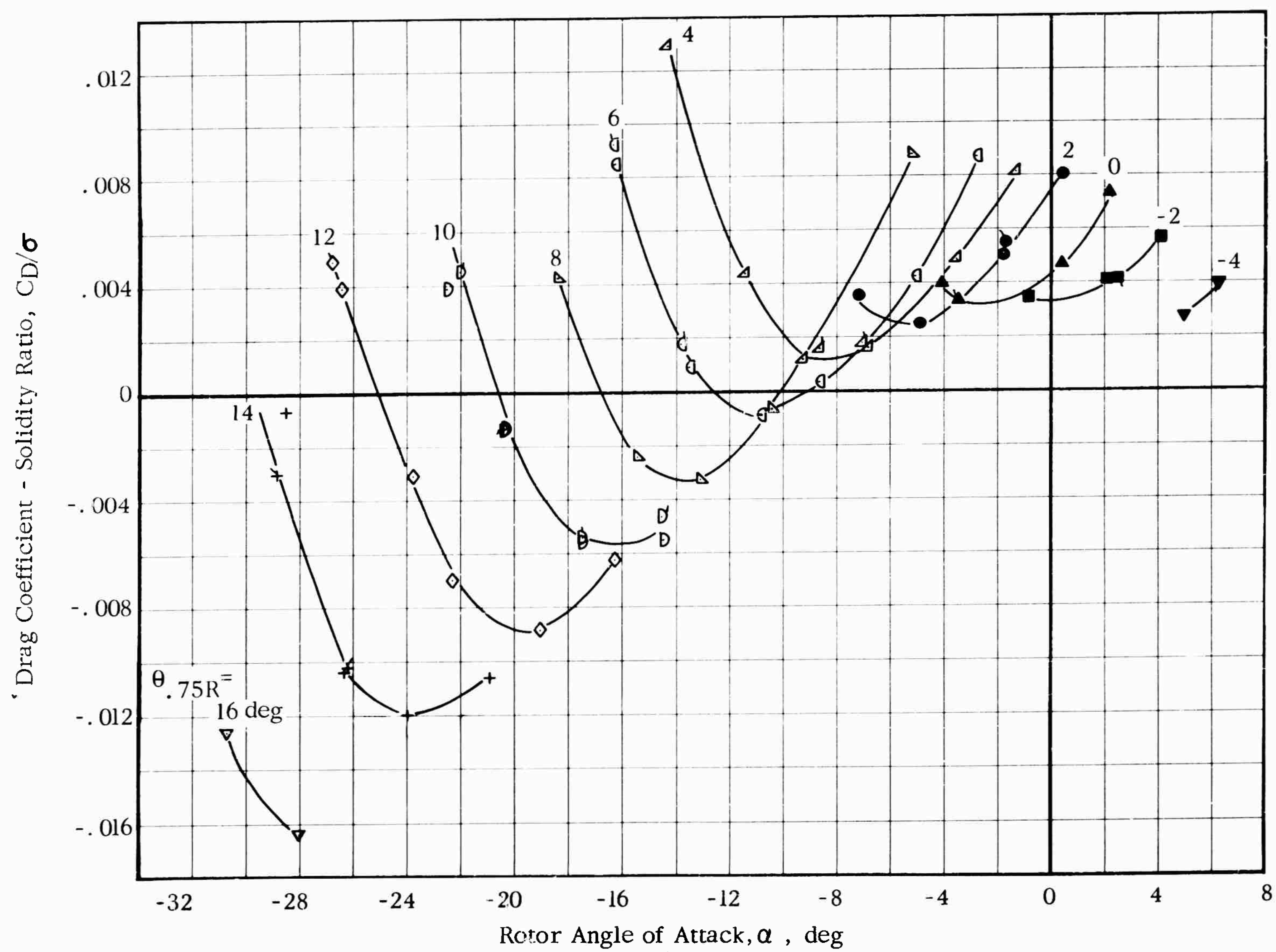
Figure 20. -Concluded



(a) C_L/σ vs α

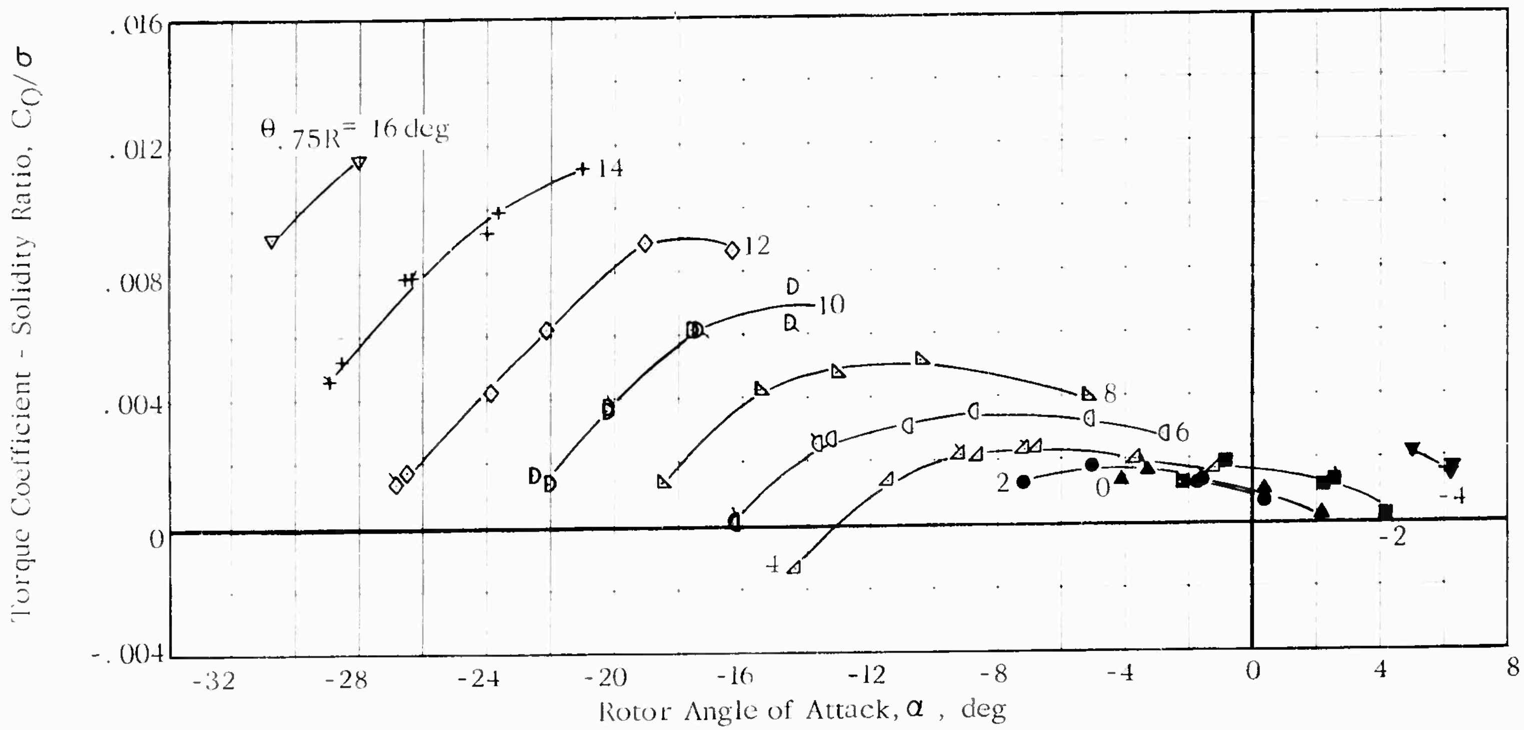
FIG. 21. EXPERIMENTAL ROTOR PERFORMANCE

V = 161 kt ΩR = 700 ft/sec μ = .39 θ_1 = -4 deg



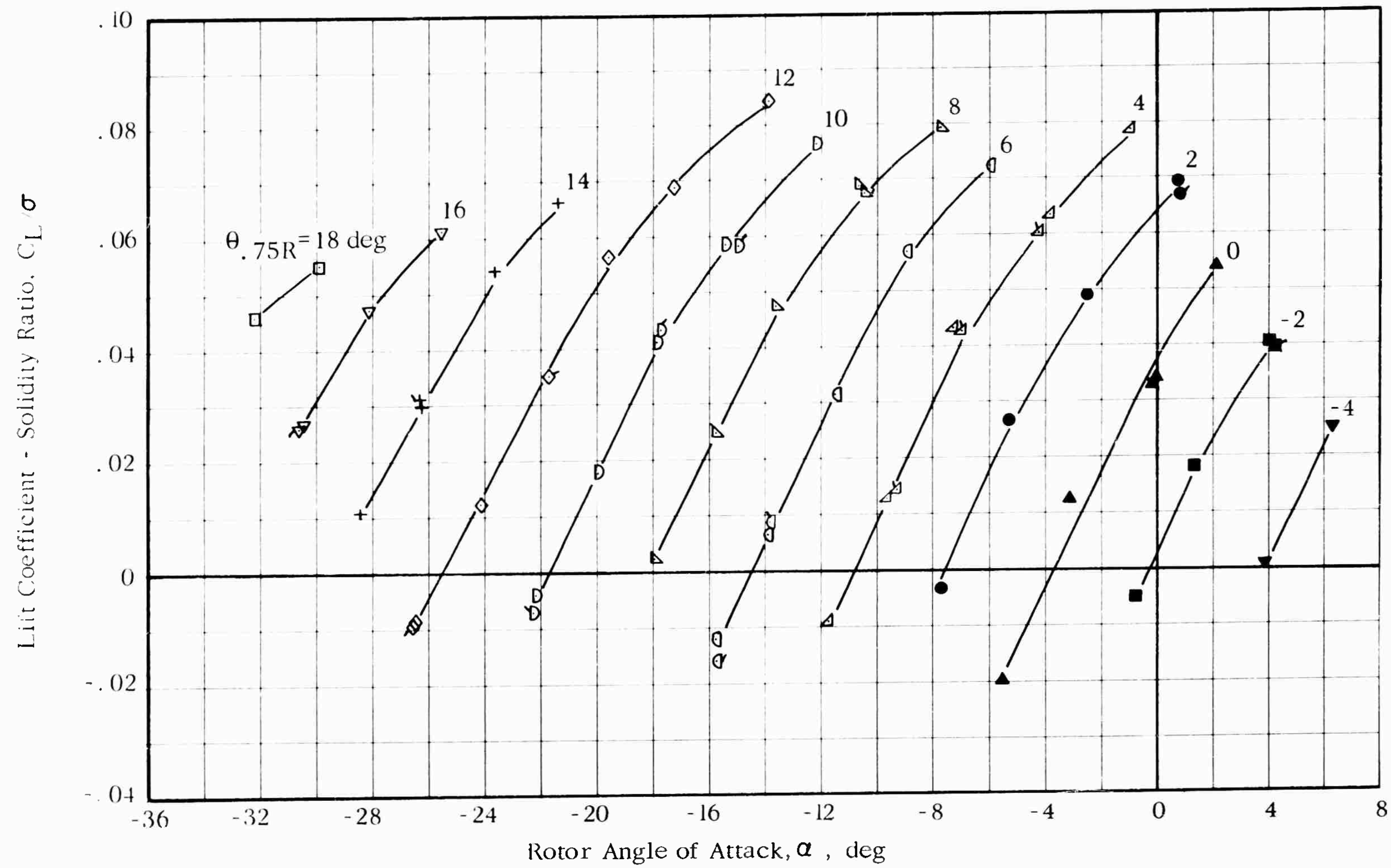
(b) C_D/σ vs α

Figure 21. -Continued



(c) C_Q/σ vs α

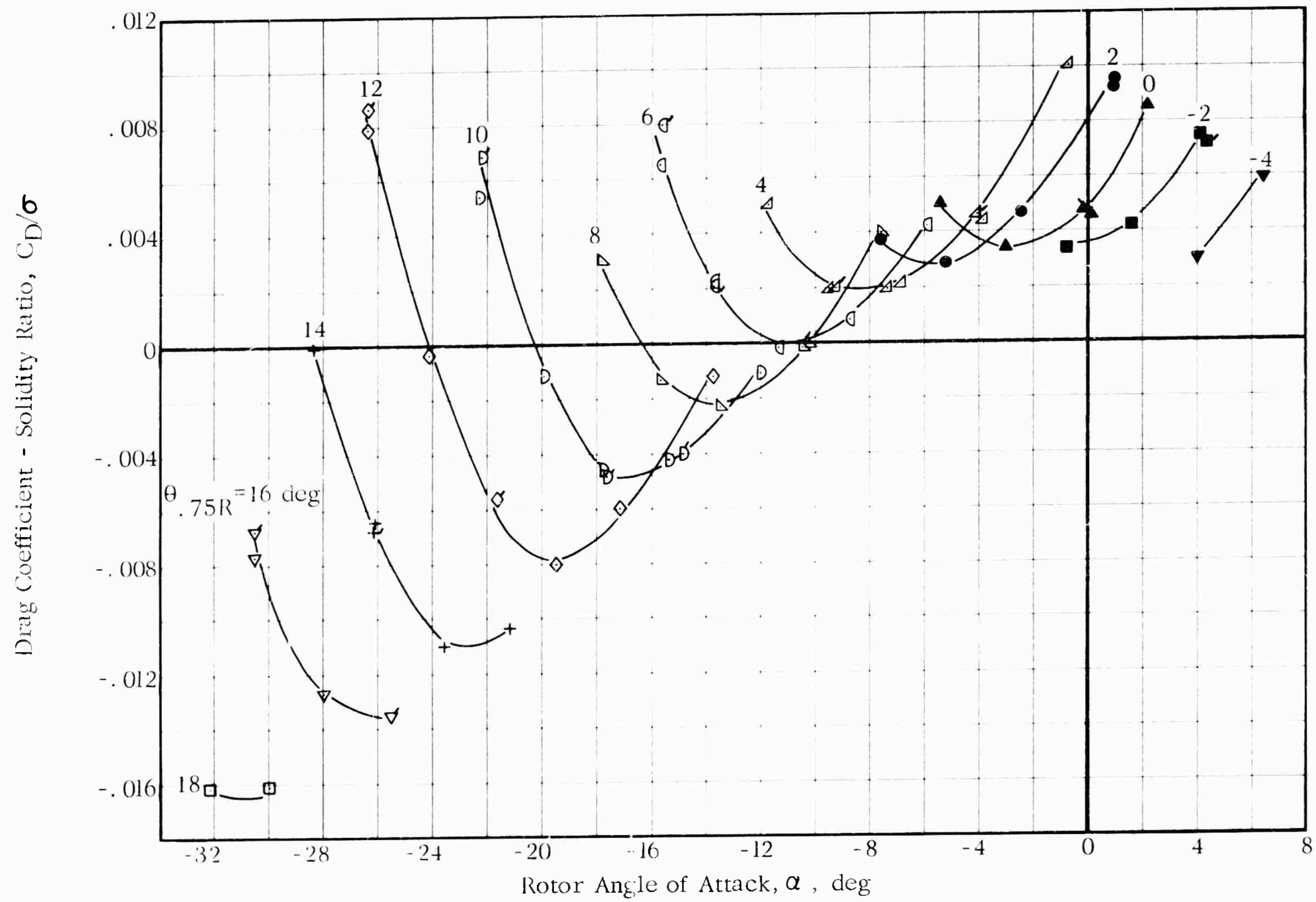
Figure 21.-Concluded



(a) C_L/σ vs α

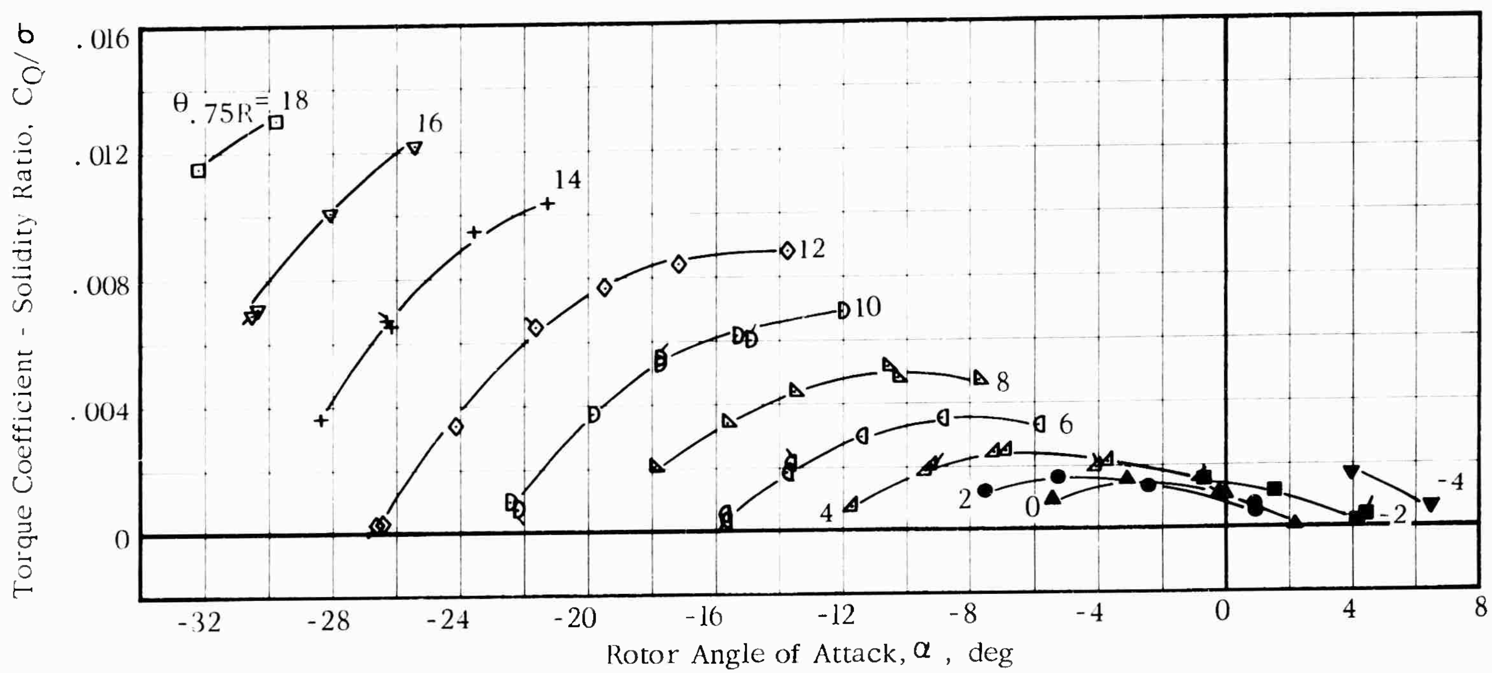
FIG. 22. EXPERIMENTAL ROTOR PERFORMANCE

V = 161 kt ΩR = 650 ft/sec μ = .42 θ_1 = -4 deg



(b) C_D/σ vs α

Figure 22. - Continued



(c) C_Q/σ vs α

Figure 22. -Concluded

APPENDIX II

ROTOR BLADE VIBRATORY STRESS

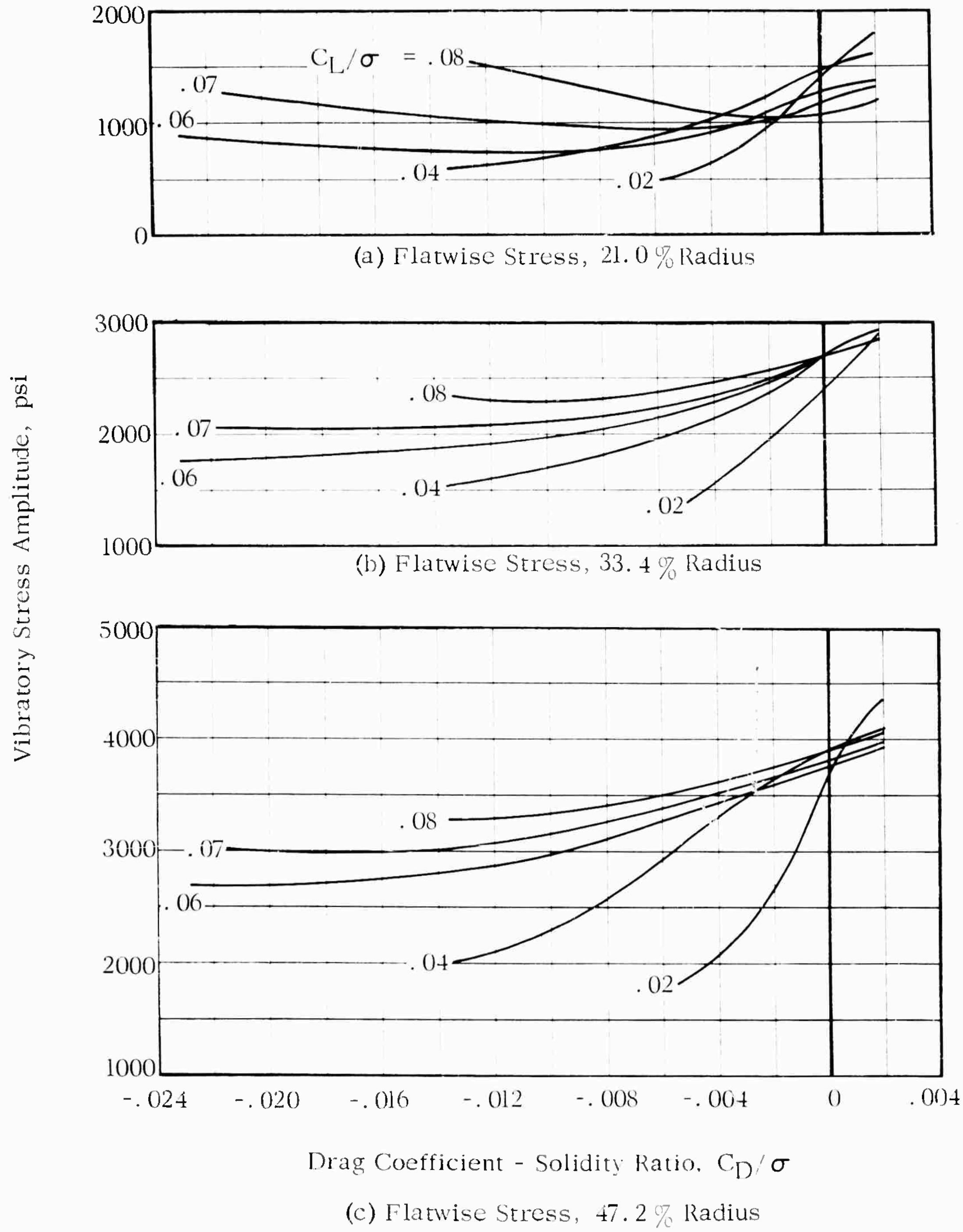
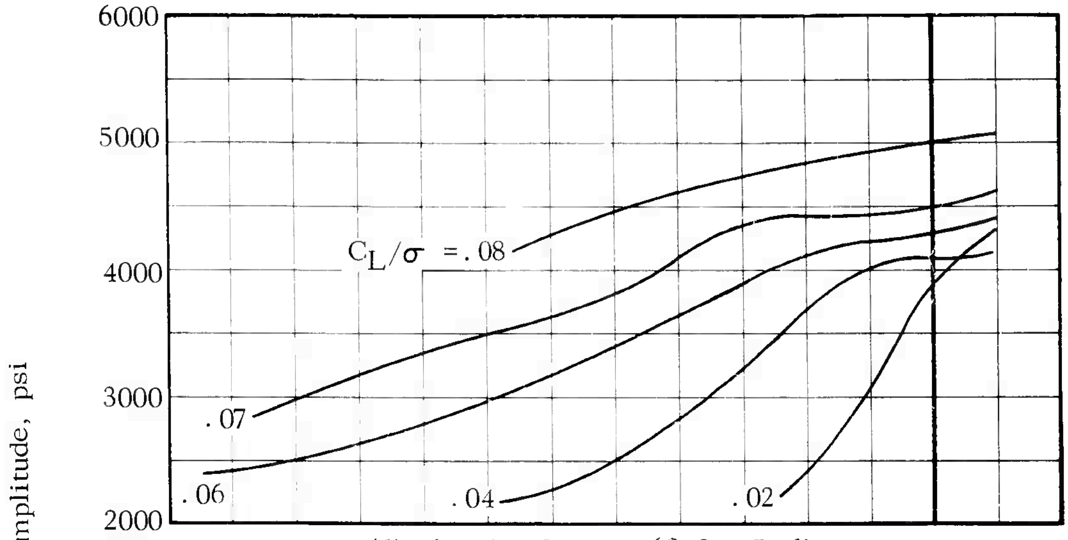
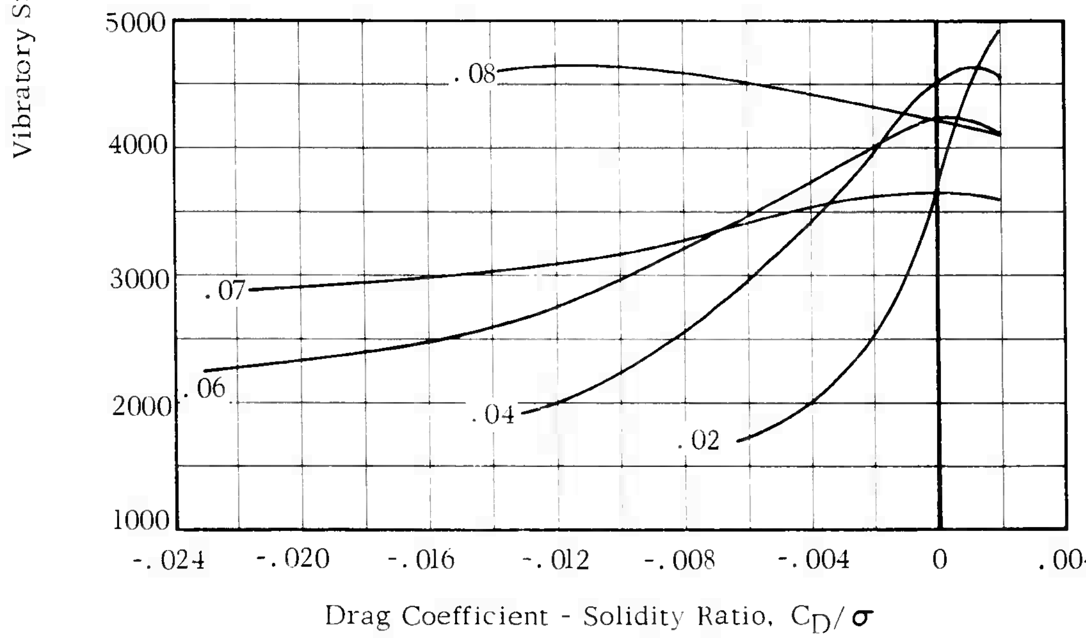


FIG. 23. EXPERIMENTAL VIBRATORY BLADE STRESS AMPLITUDE

V = 125 kt ΩR = 700 ft/sec μ = .30 θ_1 = -8 deg

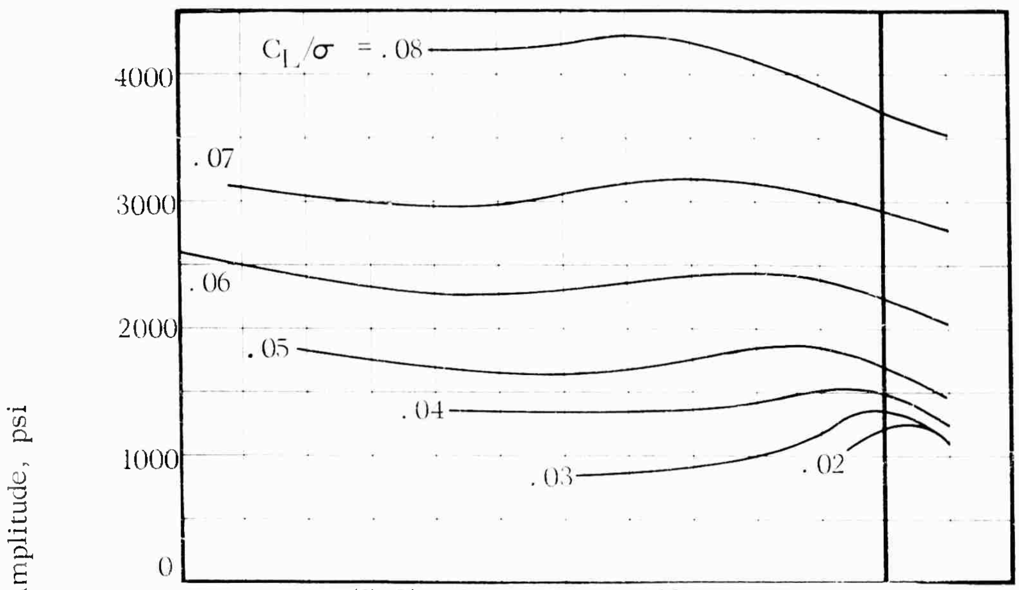


(d) Flatwise Stress, 63.9 % Radius

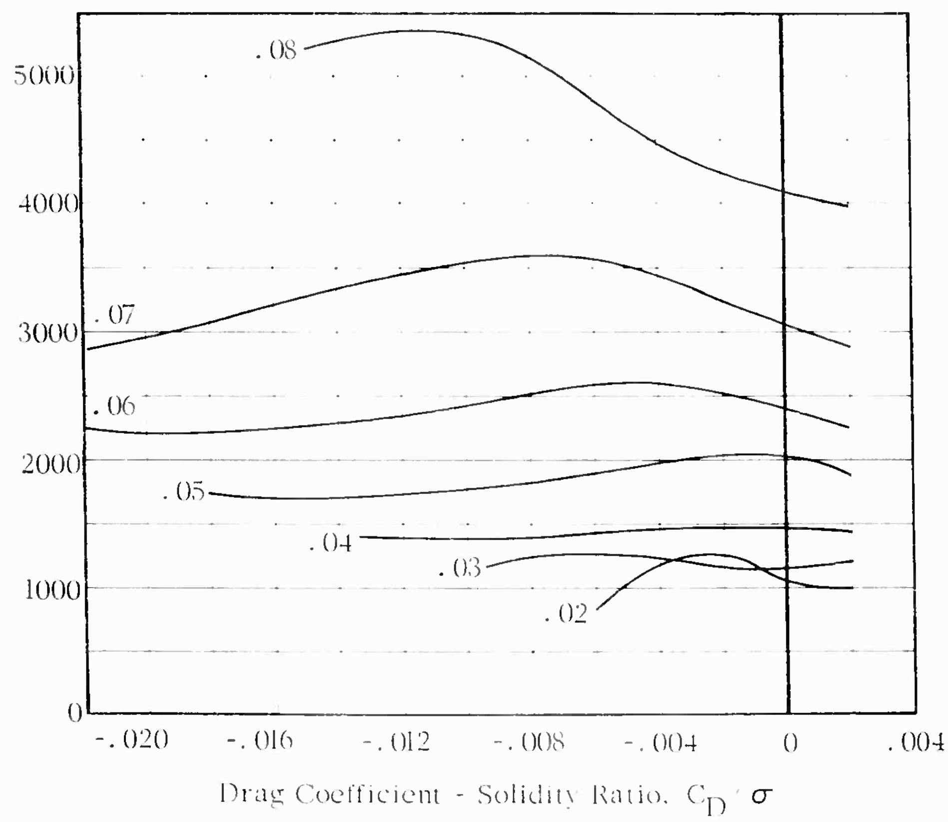


(e) Flatwise Stress, 80.5 % Radius

Figure 23. -Continued

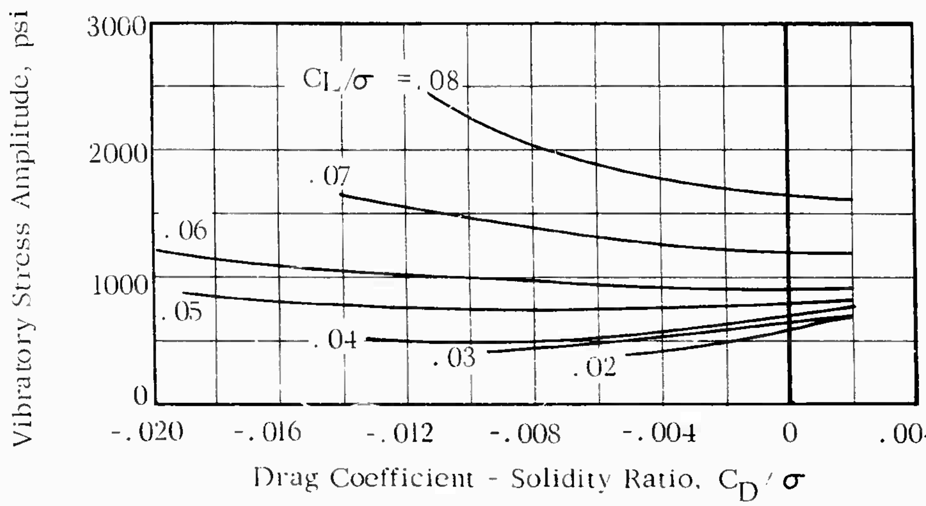


(f) Chordwise Stress, 33.4 % Radius



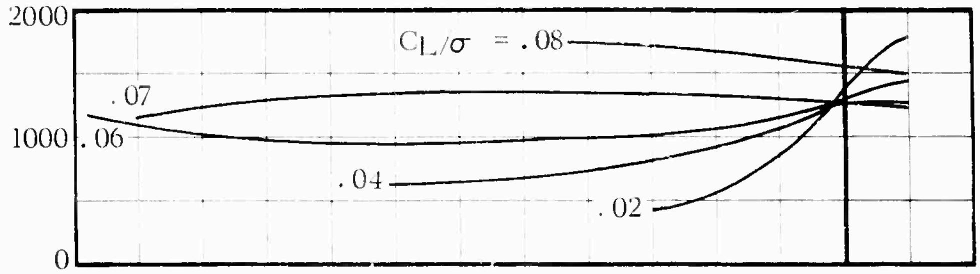
(g) Chordwise Stress, 47.2 % Radius

Figure 23. - Continued

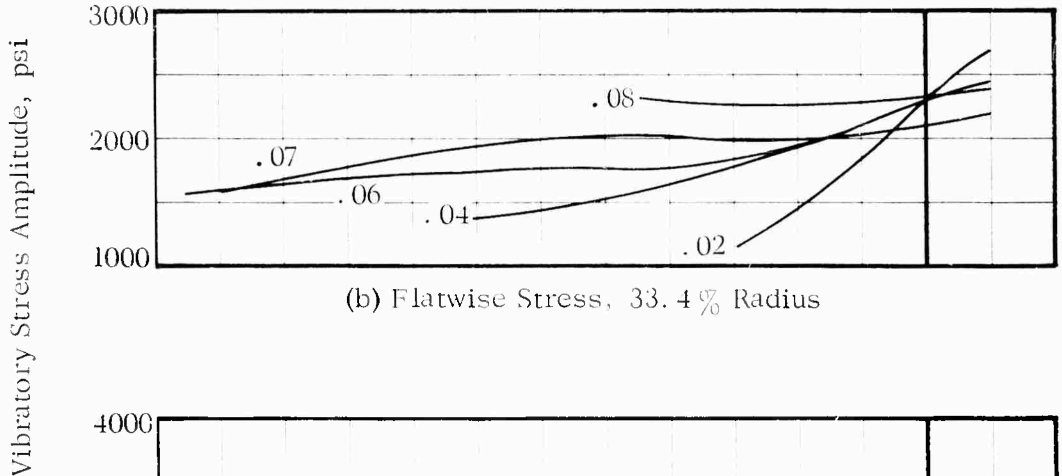


(h) Torsion Stress, 36.3 % Radius

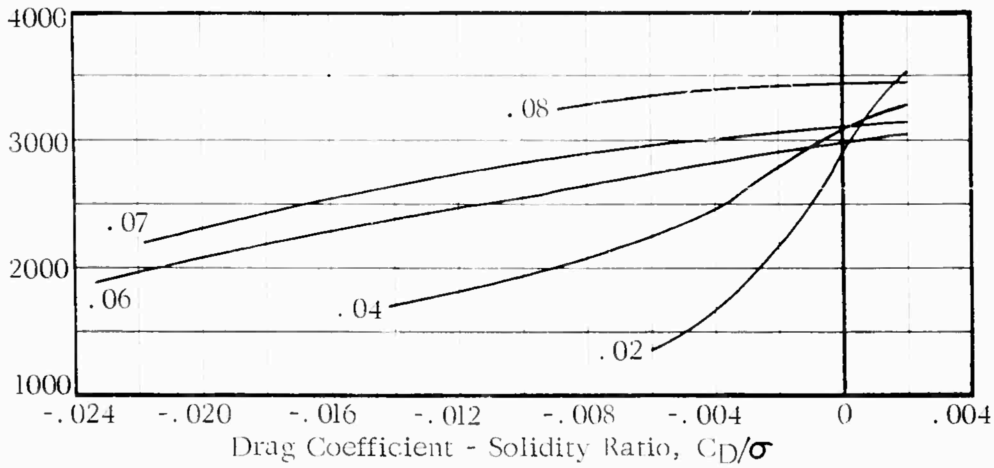
Figure 23. -Concluded



(a) Flatwise Stress, 21.0 % Radius



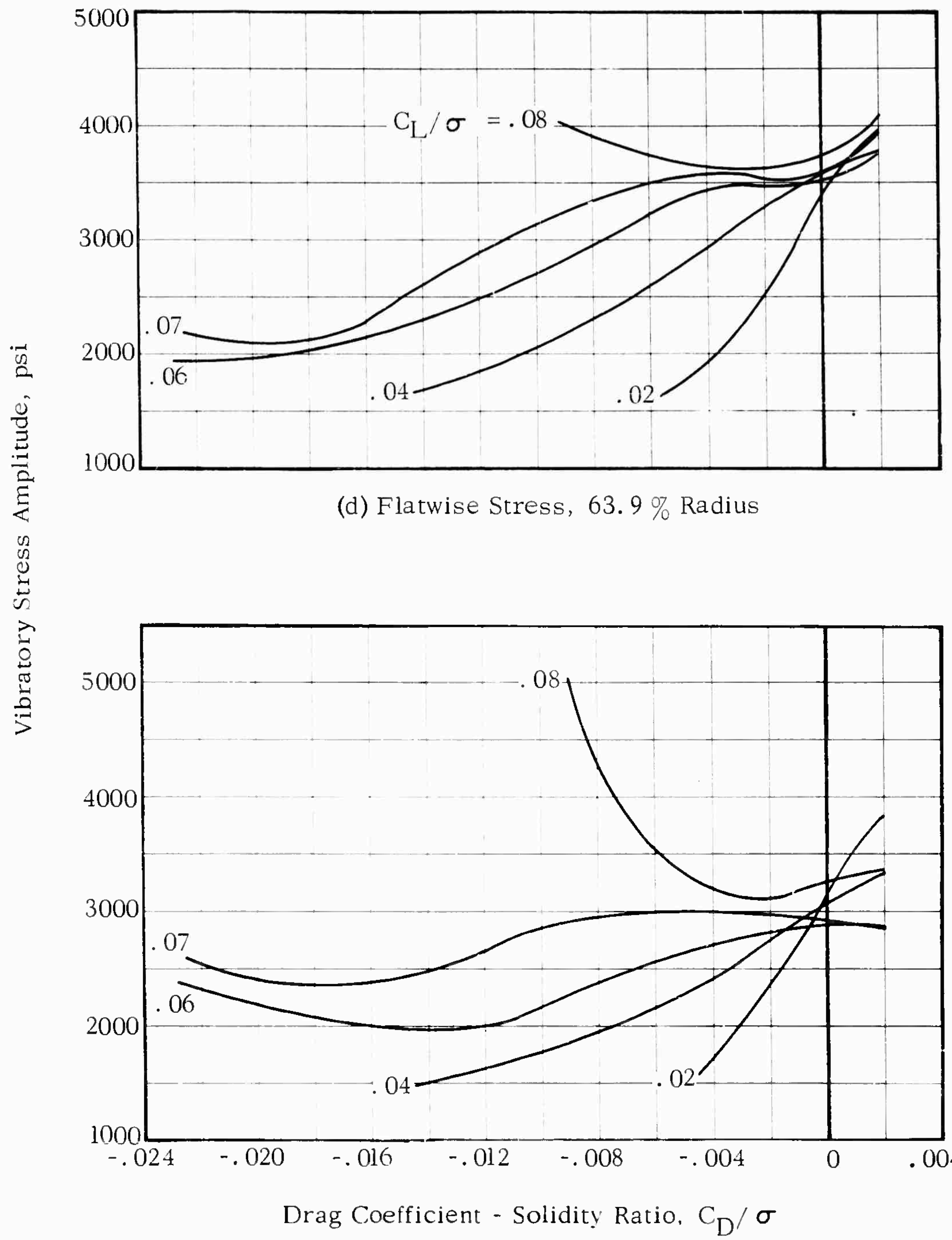
(b) Flatwise Stress, 33.4 % Radius



(c) Flatwise Stress, 47.2 % Radius

FIG. 24. EXPERIMENTAL VIBRATORY BLADE STRESS AMPLITUDE

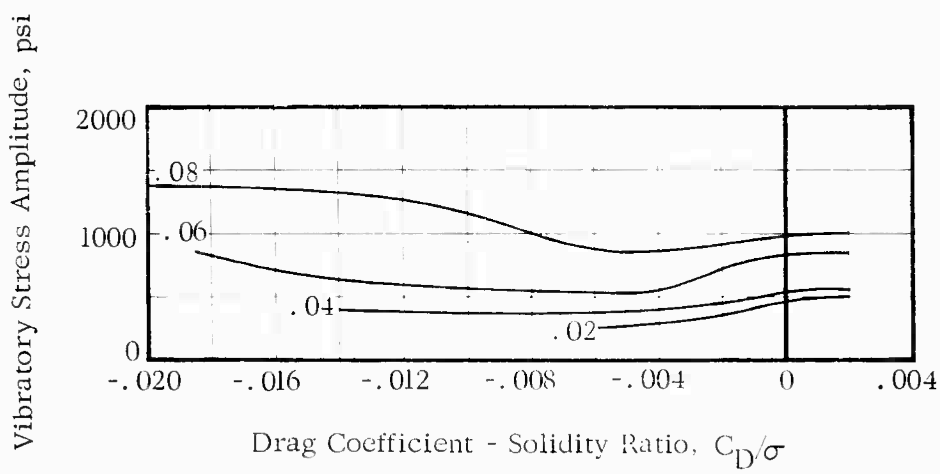
$V = 125$ kt $\qquad \Omega R = 700$ ft/sec $\qquad \mu = .30 \qquad \theta_1 = -4$ deg



(d) Flatwise Stress, 63.9 % Radius

(e) Flatwise Stress, 80.5 % Radius

Figure 24. - Continued



(f) Torsion Stress, 36.3 % Radius

Figure 24. -Concluded

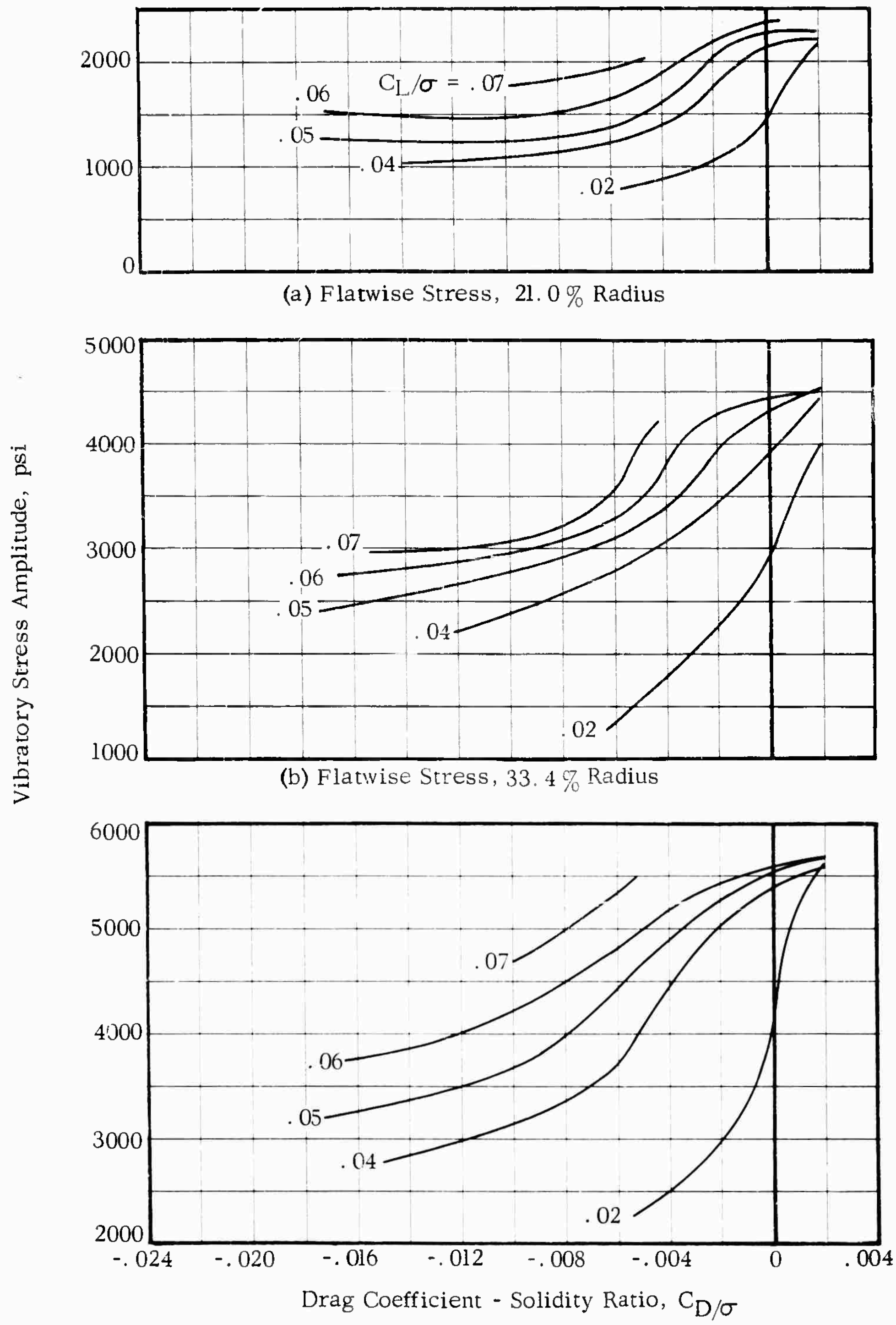
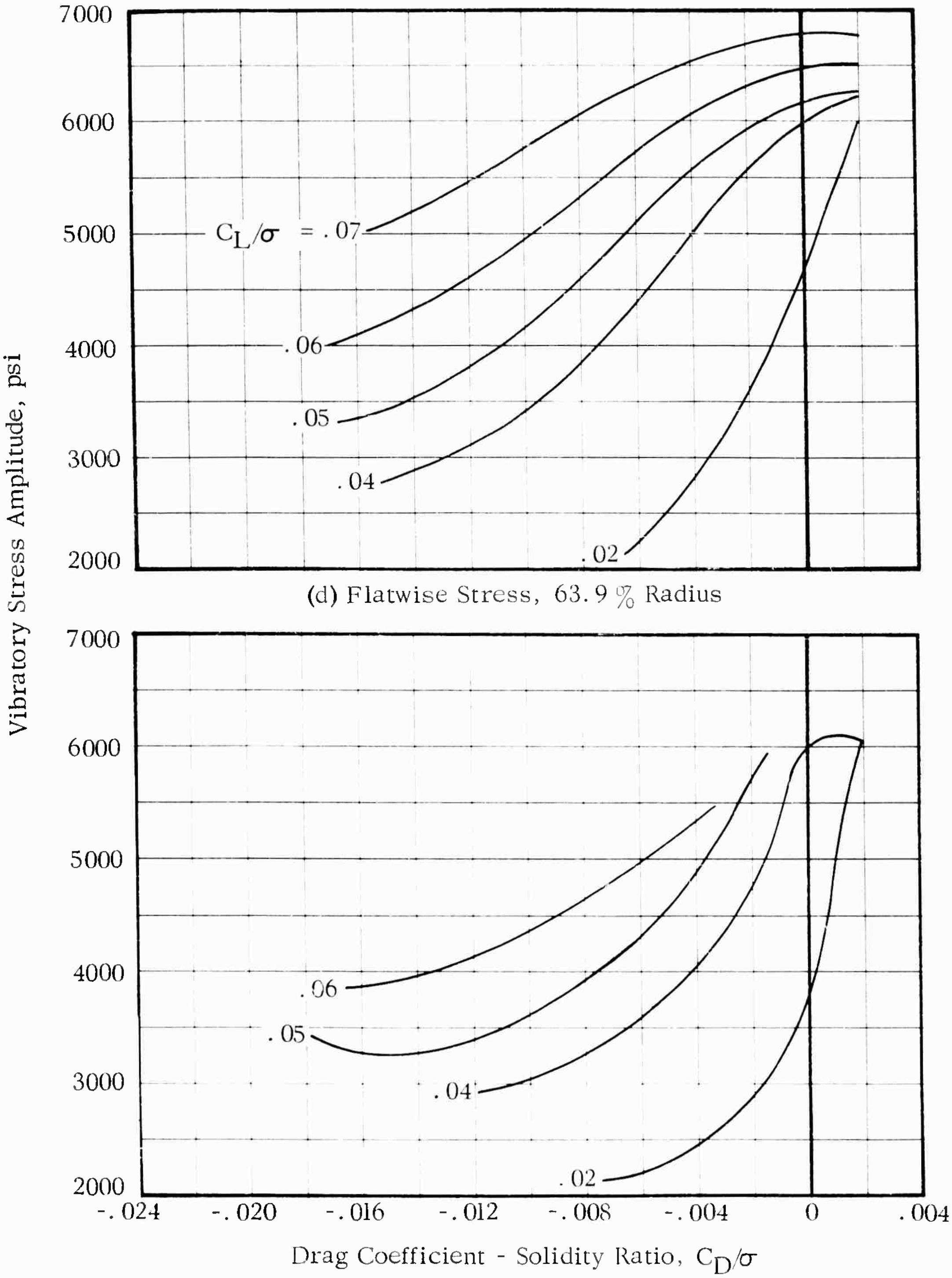


FIG. 25. EXPERIMENTAL VIBRATORY BLADE STRESS AMPLITUDE.

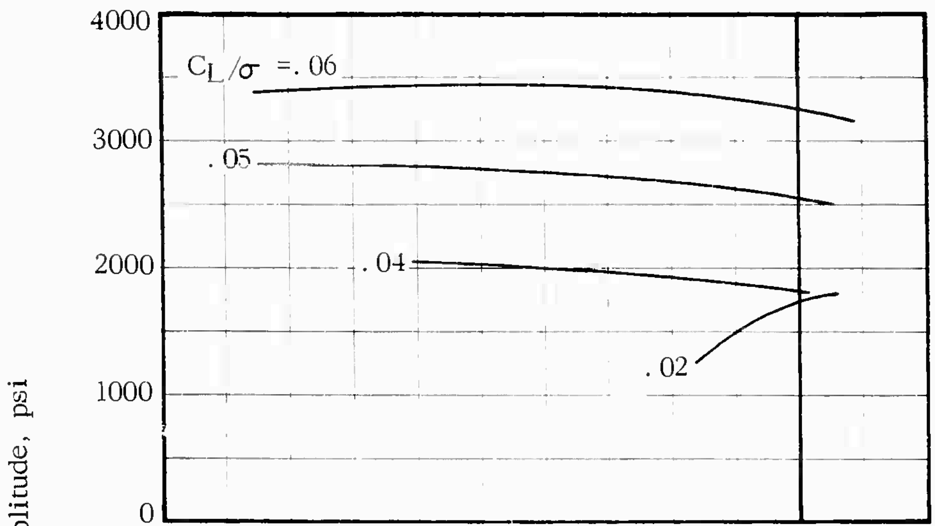
V = 161 kt ΩR = 700 ft/sec μ = .39 θ_1 = -8 deg



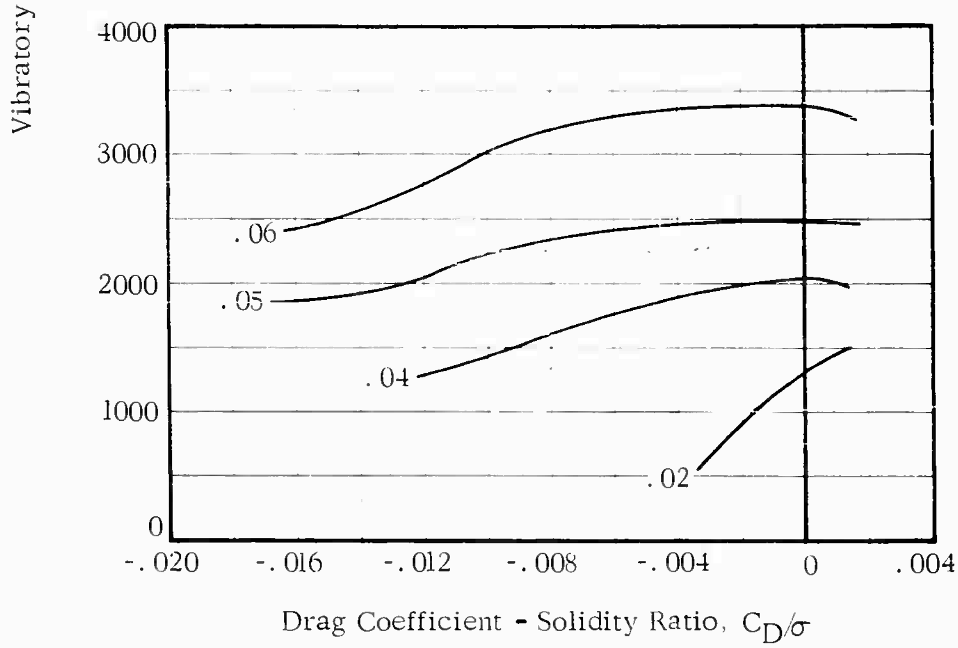
(d) Flatwise Stress, 63.9 % Radius

(e) Flatwise Stress, 80.5 % Radius

Figure 25. -Continued

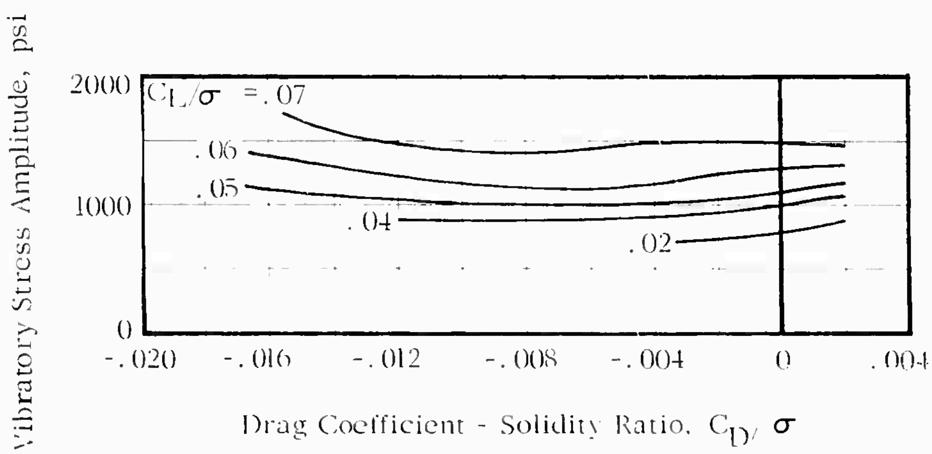


(f) Chordwise Stress, 33. 4 % Radius



(g) Chordwise Stress, 47. 2 % Radius

Figure 25. -Continued



(h) Torsion Stress, 36.3 % Radius

Figure 25. -Concluded

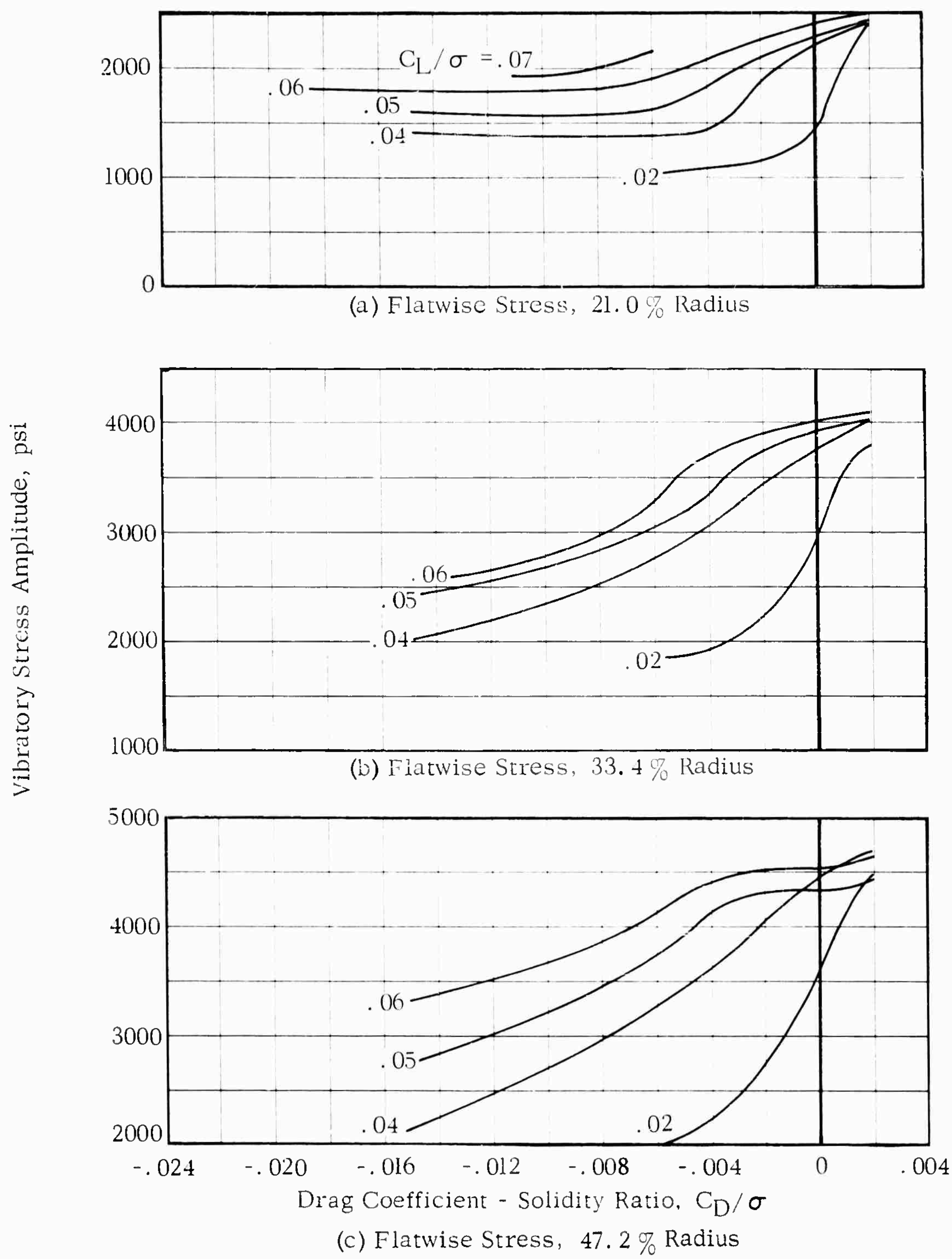
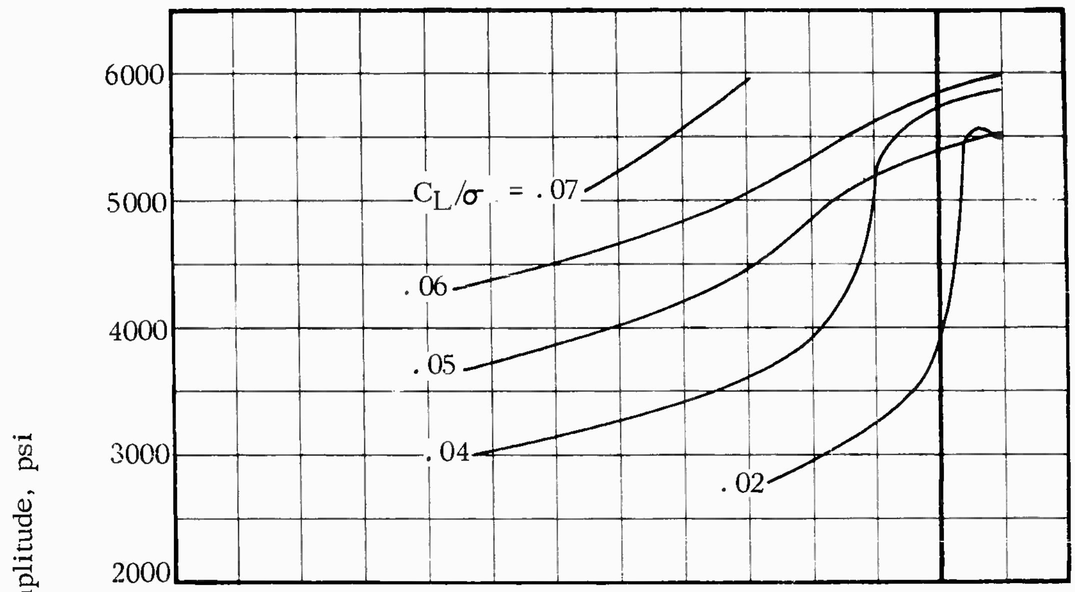
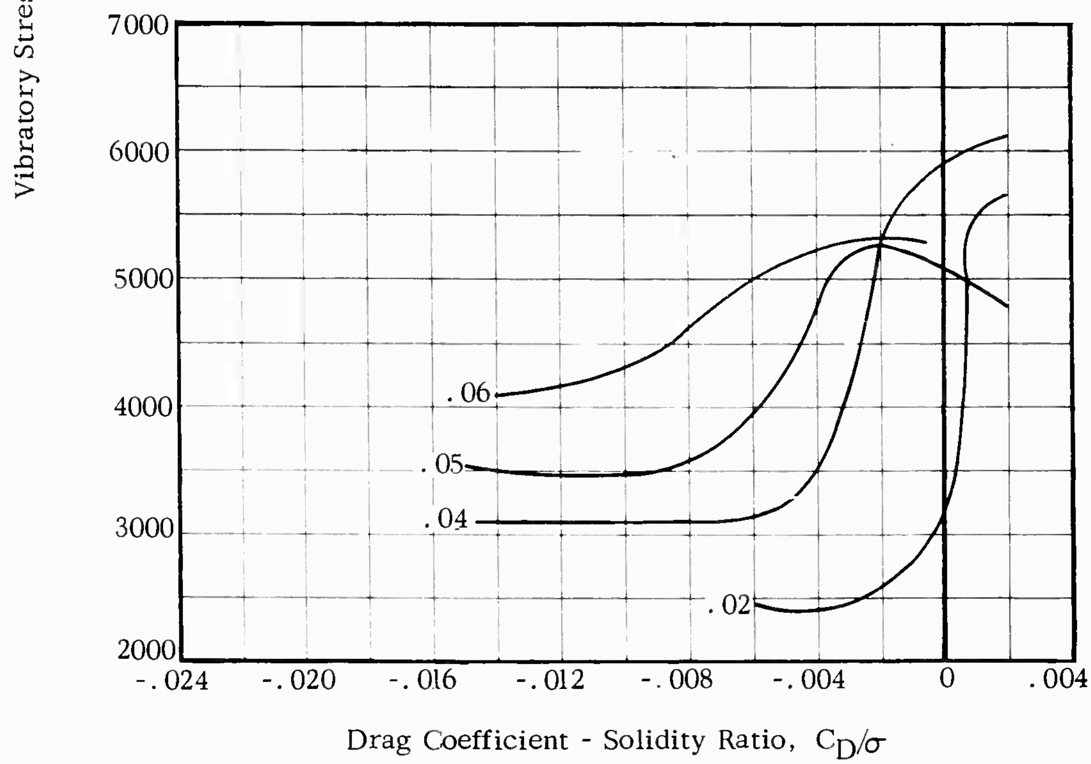


FIG. 26. EXPERIMENTAL VIBRATORY BLADE STRESS AMPLITUDE

V = 161 kt ΩR = 700 ft/sec μ = .39 θ_1 = -4 deg

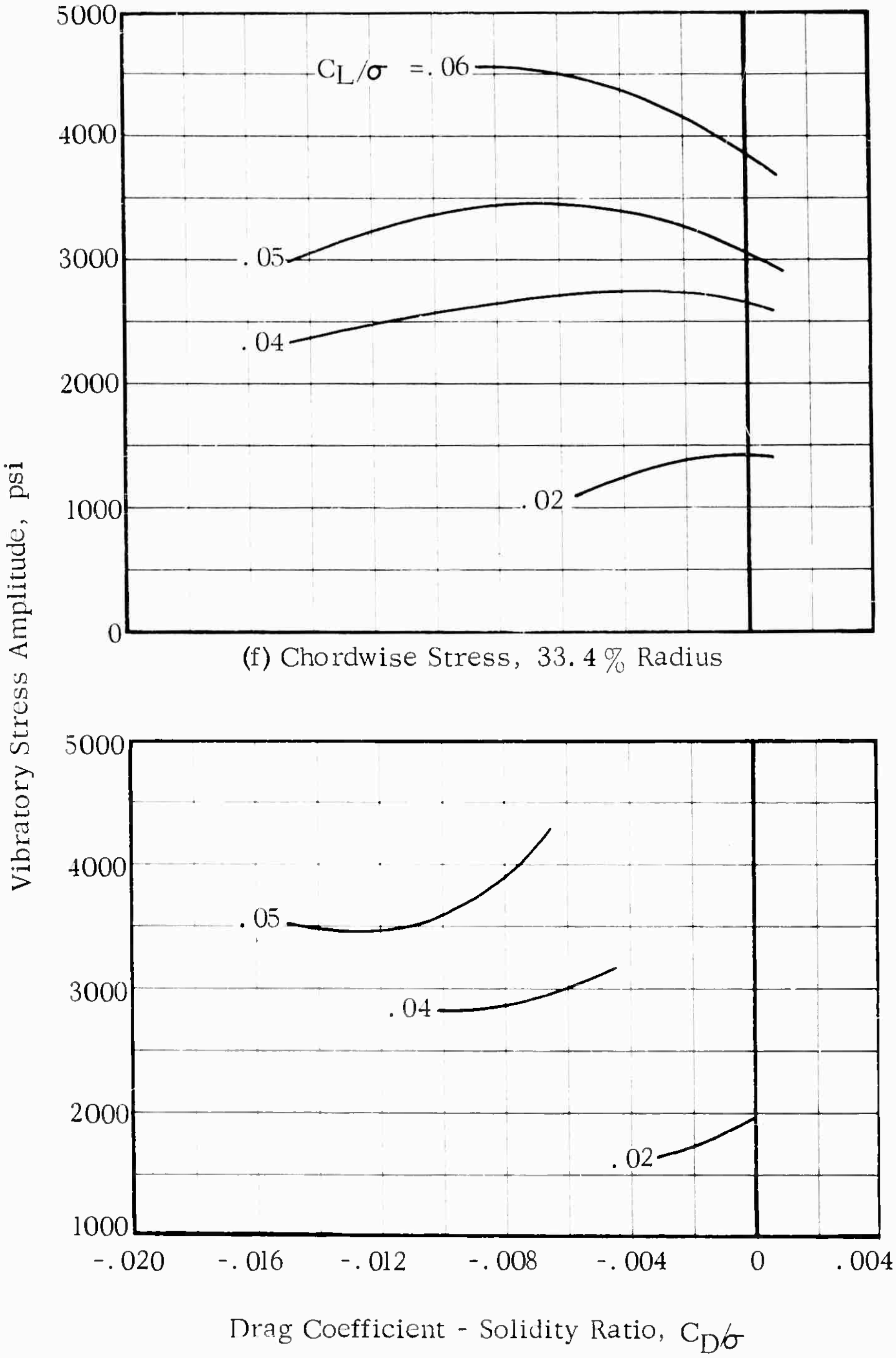


(d) Flatwise Stress, 63.9 % Radius



(e) Flatwise Stress, 80.5 % Radius

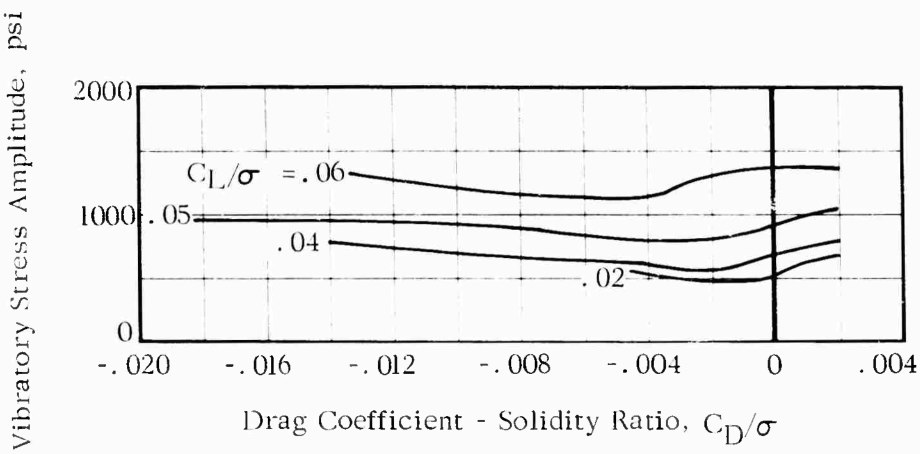
Figure 26. - Continued



(f) Chordwise Stress, 33. 4 % Radius

(g) Chordwise Stress, 47. 2 % Radius

Figure 26. - Continued



(h) Torsion Stress, 36.3 % Radius

Figure 26. -Concluded

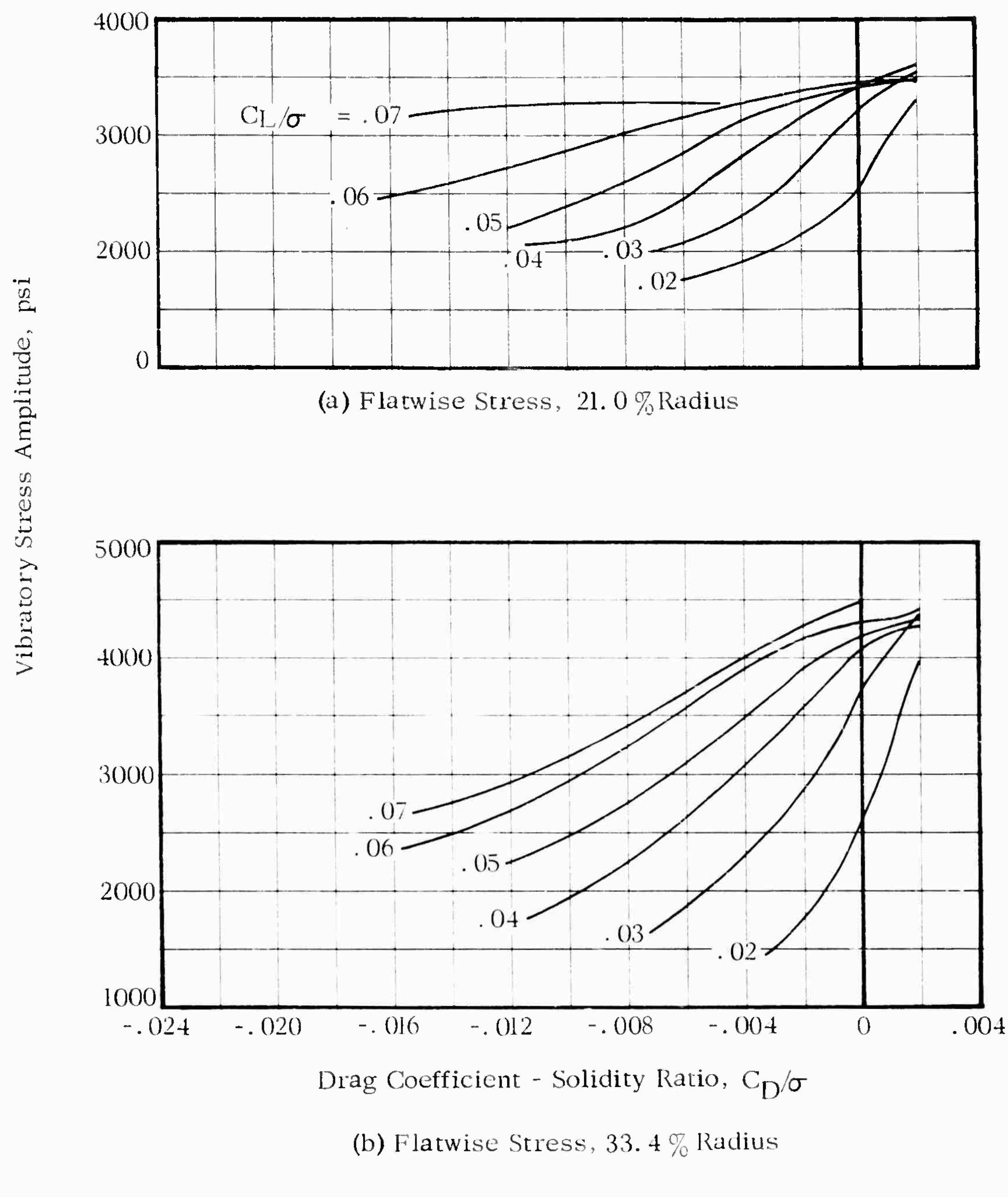
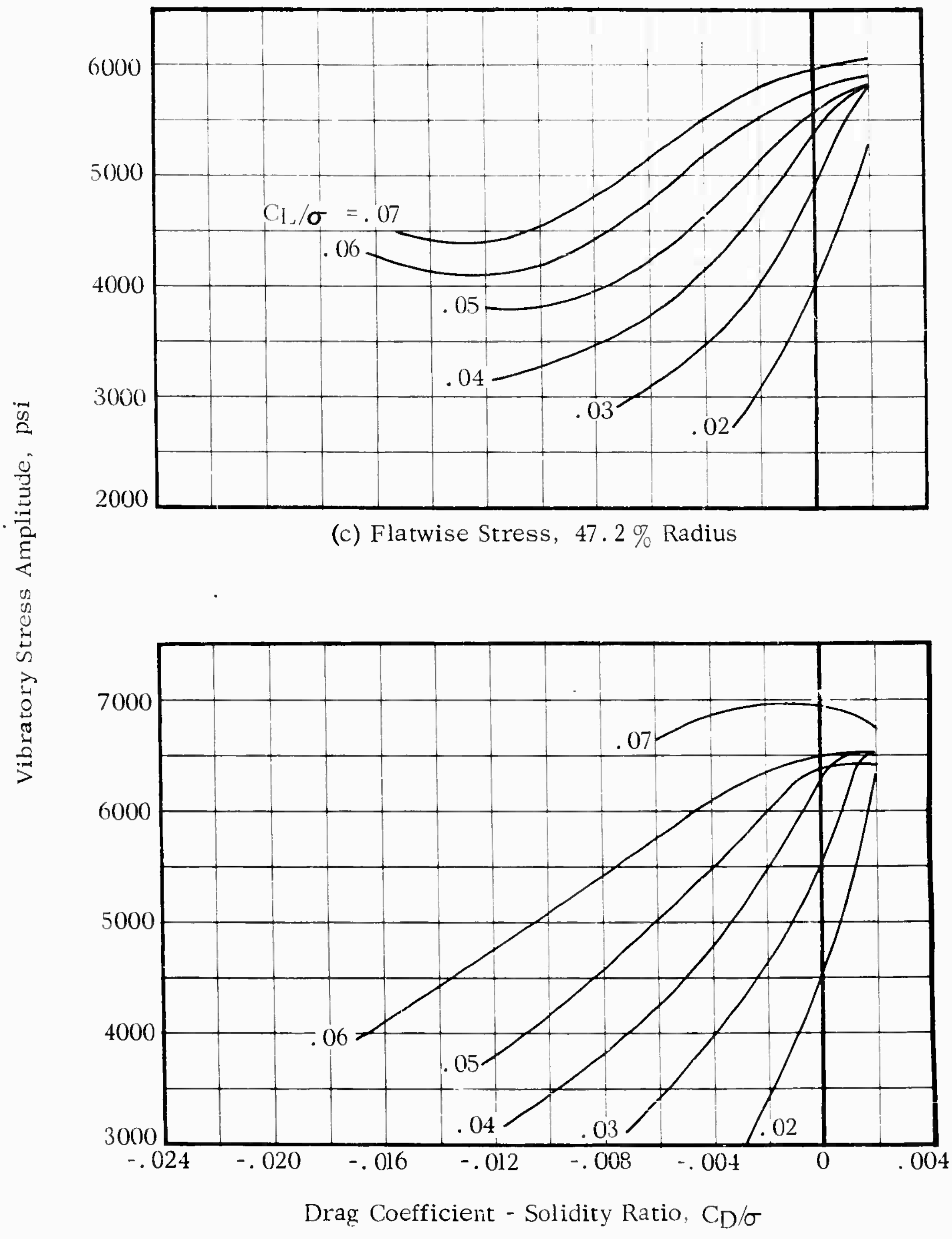


FIG. 27. EXPERIMENTAL VIBRATORY BLADE STRESS AMPLITUDE

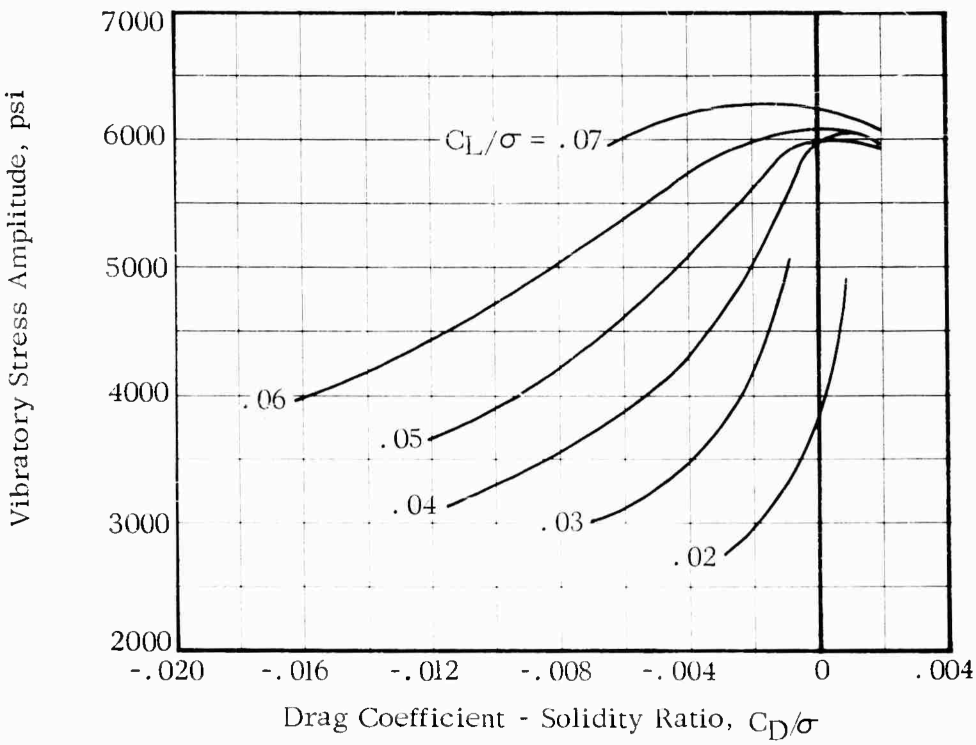
V = 161 kt ΩR= 650 ft/sec μ = .42 θ_1 = -8 deg



(c) Flatwise Stress, 47.2 % Radius

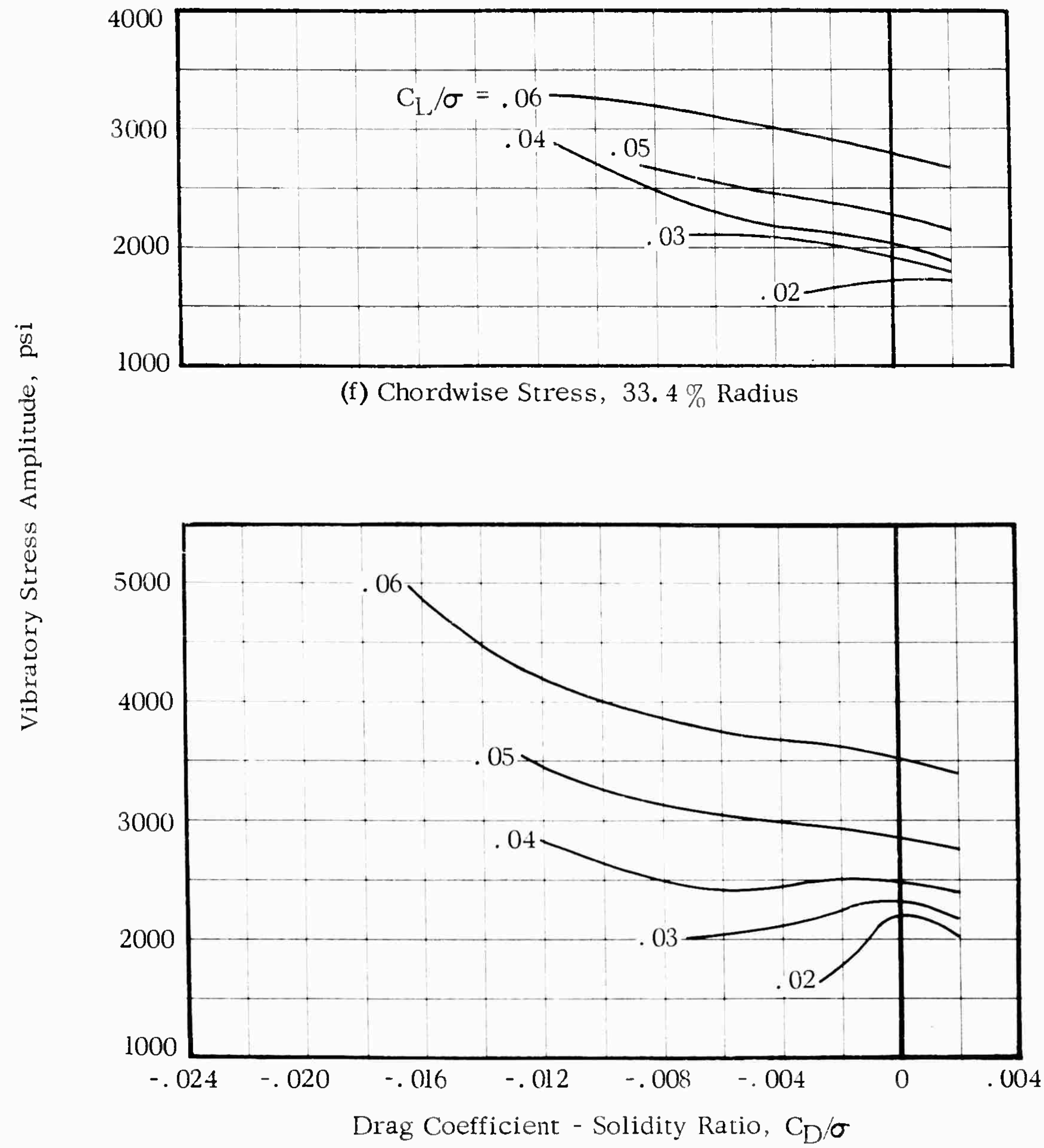
(d) Flatwise Stress, 63.9 % Radius

Figure 27. - Continued



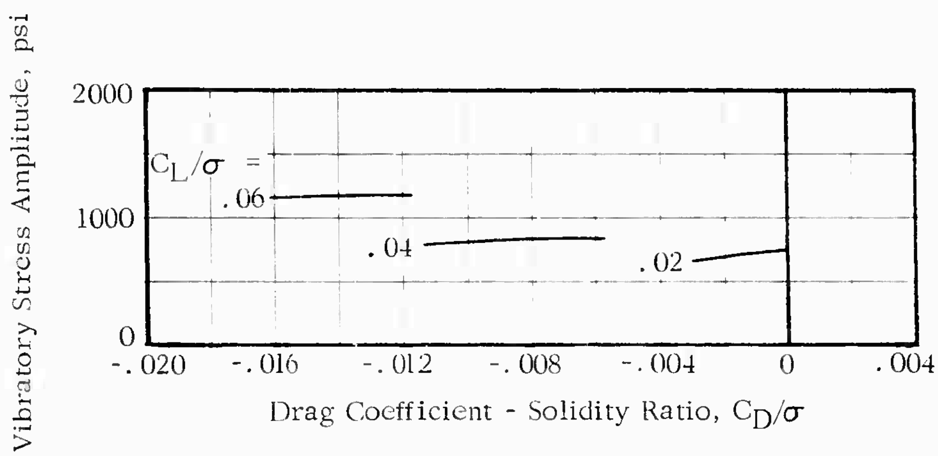
(e) Flatwise Stress, 80.5 % Radius

Figure 27. -Continued



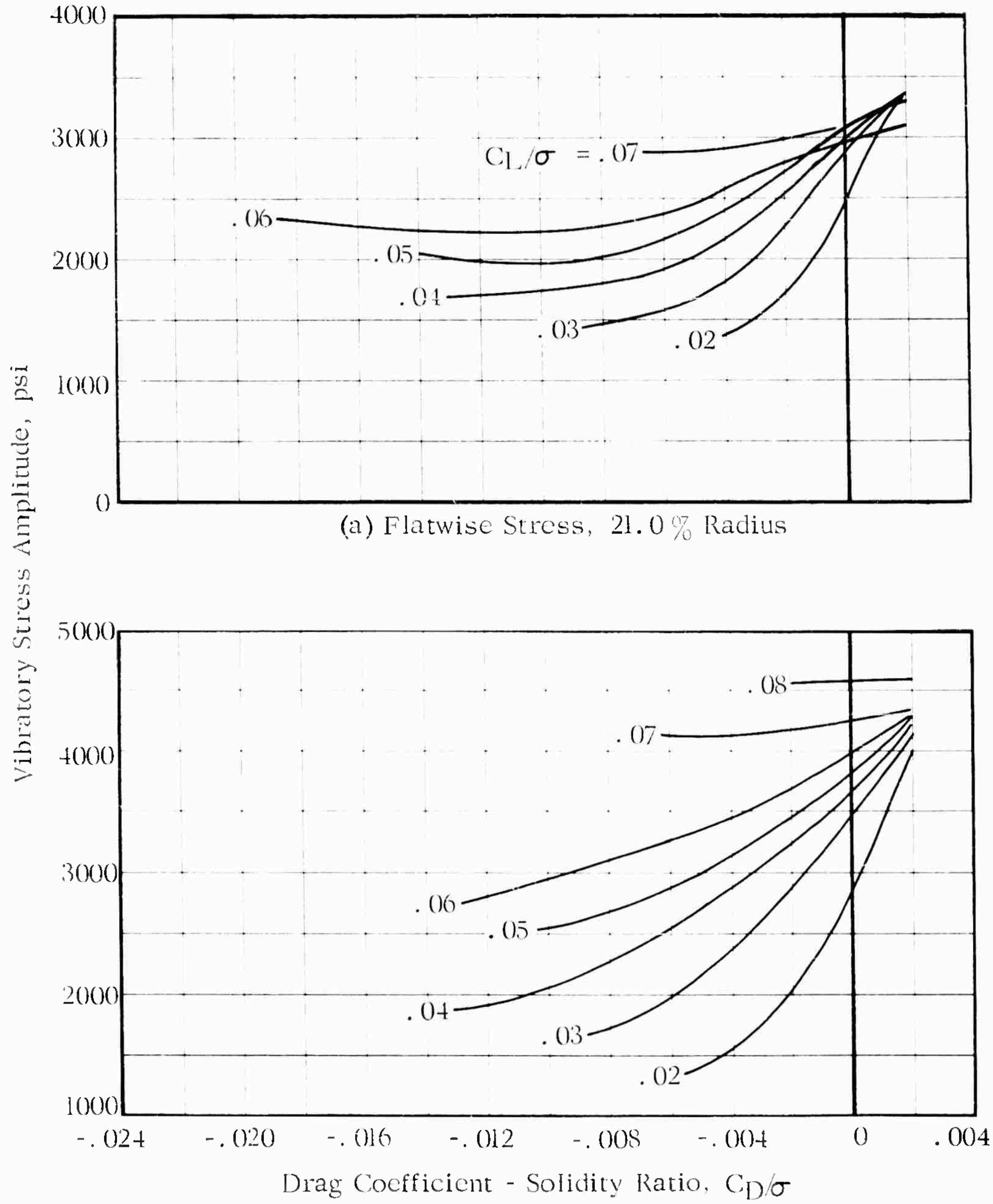
(g) Chordwise Stress, 47.2 % Radius

Figure 27. -Continued



(h) Torsion Stress, 36.3% Radius

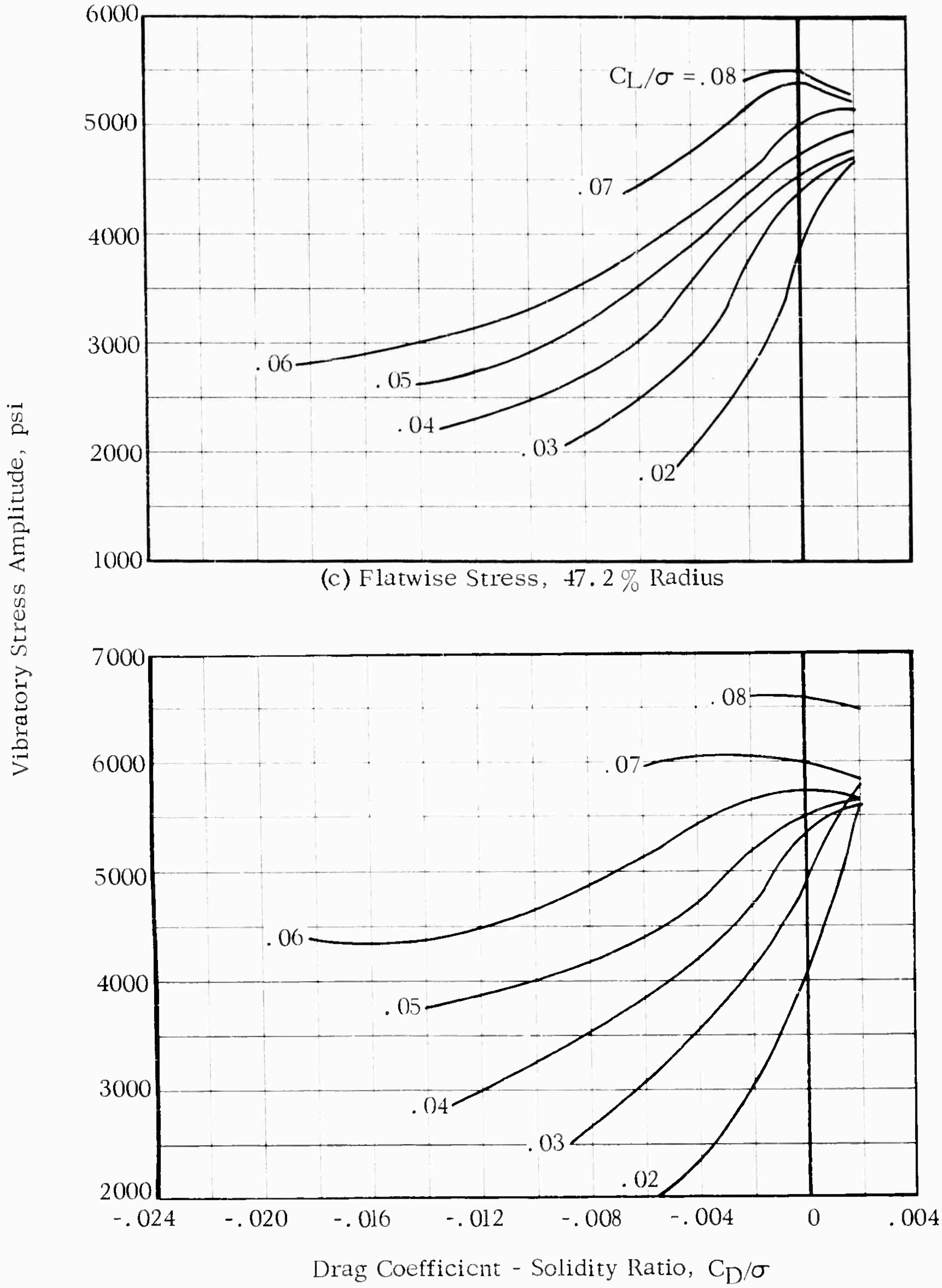
Figure 27. -Concluded



(b) Flatwise Stress, 33. 4 % Radius

FIG. 28. EXPERIMENTAL VIBRATORY BLADE STRESS AMPLITUDE

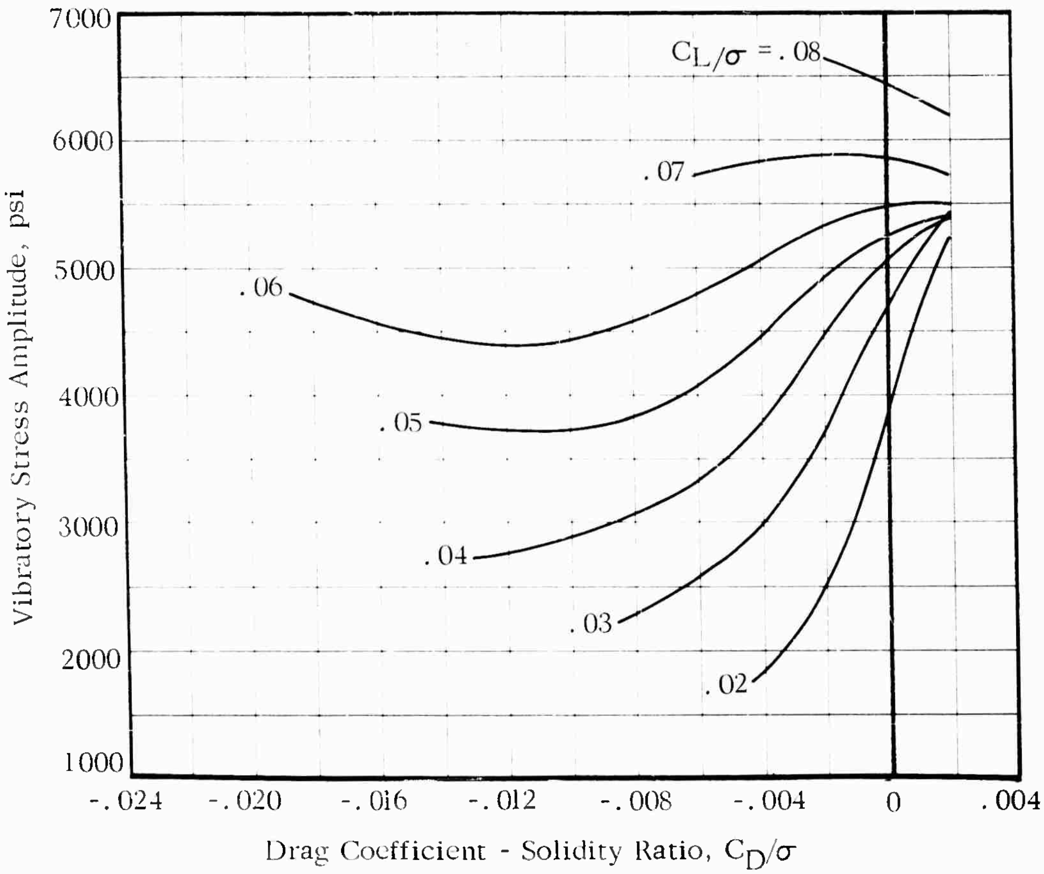
V = 161 kt ΩR = 650 ft/sec μ = . 42 θ_1 = -4 deg



(c) Flatwise Stress, 47.2 % Radius

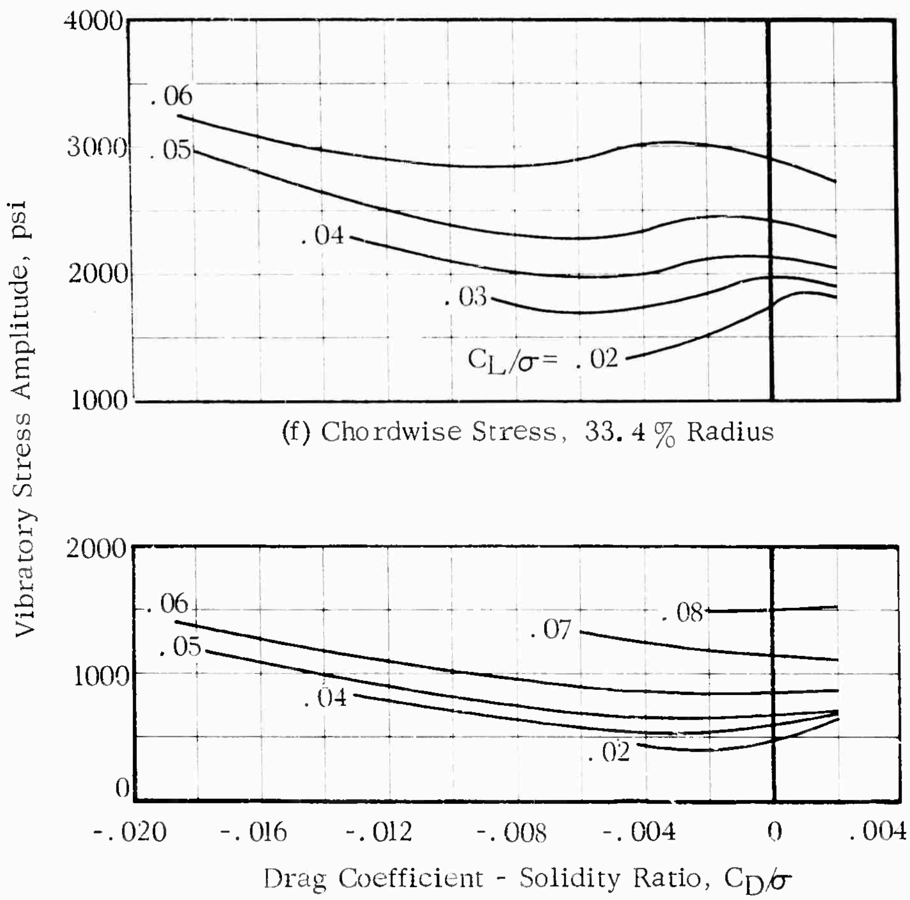
(d) Flatwise Stress, 63.9 % Radius

Figure 28. -Continued



(e) Flatwise Stress, 80.5 % Radius

Figure 28. - Continued



(f) Chordwise Stress, 33.4 % Radius

(g) Torsion Stress, 36.3 % Radius

Figure 28. -Concluded

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The investigation was sponsored by the United States Army Transportation Research Command.

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